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A JOURNAL OF EXPERIMENTAL AND THEORETICAL PHYSICS

CONDUCTED
WITH THE CO-OPERATION OF THE

AMERICAN PHYSICAL SOCIETY

BY

EDWARD L. NICHOLS,
ERNEST MERRITT, and FREDERICK BEDELL

CLXXVI

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THE

PHYSICAL REVIEW.

VOLUME IONIZATION PRODUCED BY LIGHT OF EXTREMELY SHORT WAVE-LENGTH.

By Frederic Palmer, Jr.

Introduction.

In 1900 P. Lenard[1] showed that in addition to the well-known Hallwachs effect, or ionization produced at a charged metallic surface when struck by ultra-violet light, there existed also a volume effect which took place in the gas itself, and could be detected at some distance (50 cm.) from the source of illumination. He employed a spark from an induction coil between terminals of aluminum. Since the light from this spark passed through a quartz window and a layer of air more than one centimeter thick it is very unlikely that it contained any effective rays of wave-length less than λ 1800. It seemed worth while, therefore, to investigate the effect of that part of the spectrum discovered by Schumann[2] which lies on the more refrangible side of λ1800. The present research was accordingly begun in February, 1904.

Lenard[1] showed that the ionization observed by him was closely connected with the absorption of ultra-violet light by the gas under investigation. Therefore, since it is known that wave-lengths in the Schumann region are completely absorbed by a thin layer of air at atmospheric pressure, the object of this research was to find out if possible whether this absorption was accompanied by ionization; and if so, whether this result increased as the wave-length of the effective light diminished.

[1]Ann. Phys., 1, p. 486, 1900; 3, p. 298, 1900.

[2]Smiths. Contrib. No. 1413, 1903; T. Lyman, Astroph. Journ., 23, p. 181, 1906.

E. Bloch[1] has shown that volume ionization produced by the light from an aluminum spark is greatly reduced if the gas under investigation is filtered through a plug of cotton wool; and he therefore has ascribed the effect observed by Lenard to photo-electric particles held in suspension in the gas, and not to ionization of the gas itself. More recently J. Stark[2] from other considerations has stated that the Lenard effect is probably due to photo-electric particles in the gas. He has also shown that volume ionization may be produced by the light from a quartz mercury lamp in certain organic vapors. The effective wave-lengths lay in the region between $\lambda 1850$ and $\lambda 3800$. He obtained currents through the vapors as large as 5×10^{-9} amp. under a pressure of about 50 mm.

J. J. Thomson and W. C. McKaye[3] have found that the light from a Wehnelt hot lime-covered cathode produces ionization in air, carbon dioxide, and ammonia; but the currents obtained by them were excessively small.

In this paper it will be shown that comparatively large currents may be obtained in air at atmospheric pressure when the extremely short wave-lengths which lie in the Schumann region are used as a source of illumination.

Before undertaking the main part of the research, Lenard's experiments were repeated both with the steam-jet and with a cylindrical condenser as the detecting apparatus. A Dolezalek electrometer instead of an electroscope was used to measure the leak between the cylinders. The chief sources of error were : (1) irregularities in the illumination produced by the aluminum spark; (2) the Hallwachs effect, which was eliminated by the proper use of soap solution; (3) photo-electric fatigue,[4] which resulted in the falling off of deflections obtained successively in the electrometer under apparently similar conditions.

GENERAL ARRANGEMENT.

Since it is purposed to employ the very short wave-lengths in the Schumann region, the form of the source of light is of the

[1]Comptes Rendus, 146, 17, p. 892.

[2]Phys. Zeitsch., 10, 18, p. 614.

[3]Proc. Comb. Phil. Soc., 14, p. 417, 1908.

[4]Cf. Hallwachs, Phys. Zeitsch., 21, p. 766, 1906.

utmost importance. It has been shown[1] that, when the secondary of a transformer is connected without additional capacity to the electrodes of a hydrogen-filled discharge tube containing traces of hydrocarbons, the excitation of the tube gives rise to carbon bands extending from the ultra-violet down to λ1700, and to strong hydrogen lines from λ1650 to λ1250. It was therefore determined to use a tube of this type as the source of illumination. While it is recognized that the carbon bands are capable of producing ionization, this investigation is chiefly concerned with the properties of the shorter waves; and therefore in order to get rid, as much as possible, of the effect produced by the carbon bands the tube was always carefully washed out with pure dry hydrogen several times before use.

The apparatus for producing ionization consisted essentially of three parts: (1) the discharge tube, (2) the screen cell, (3) the ionization chamber (see Fig. 1). The discharge tube *A* was a duplicate of the one already described by Lyman.[2] It could be exhausted by a mercury pump and filled with dry hydrogen from a small electrolytic generator. The pressure within could be measured by a McLeod gauge. The tube was excited from the secondary of a small transformer, the primary of which used about 4 amp. from a 110-volt A.–C. lighting circuit. The current through the tube, as measured by Pierce's crystal rectifier,[3] proved to be between .03 and .04 amp.

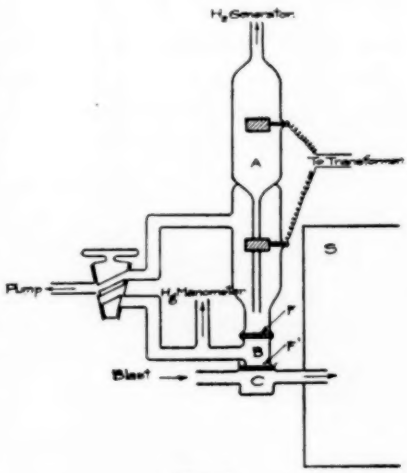


Fig. 1.
Apparatus for producing ionization.

The screen cell *B* was used as a diaphragm to cut off more or less of the effective rays according as the pressure in it was varied.

[1] T. Lyman, Astroph. Journ., 23, p. 181, 1906.
[2] *Loc. cit.*
[3] PHYS. REV., 25, p. 31, 1907.

It was 1 cm. in diameter and 1.0 cm. thick, and was separated from the discharge tube by a window of clear white fluorite F 1 mm. thick cemented with Khotinski cement. Ordinarily oxygen was used in the cell as an absorbing gas because its behavior was found to be more regular, and its absorption was better known than that of other gases. Dry oxygen could be admitted to the cell from a small electrolytic generator, and the pressure could be read either upon a closed mercury manometer or the McLeod gauge. A three-way stop-cock connected either the cell or the discharge tube to the mercury pump.

Another clear fluorite window F' 1 mm. thick separated the screen cell from the ionization chamber C, but the latter was arranged to slip over F' before being cemented in place so that the under surface of F' could be brought to a level with the side tubes of C. A blast of the gas under investigation could be maintained through C so that the ions, which were formed in this chamber, could be speedily swept away into the testing cylinders. The volume of the chamber was 1.4 c.c., and the distance between its center and the test cylinders 3 cm. Early in the investigation an ionization chamber was used which was open at the bottom so that a vessel containing mercury covered with soap solution could be raised from below to close the opening, and thus prevent surface ionization. However the soap solution was found to be the source of many irregularities in readings obtained, and so the form shown in Fig. 1, made of glass, was finally adopted. A comparison of readings obtained with the two chambers showed almost identical results, which may indicate that the ionization produced by light

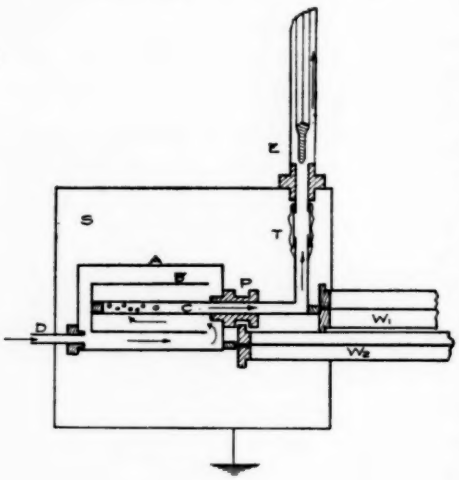


Fig. 2.
Testing apparatus.

of extremely short wave-length is confined to a region very close to the fluorite window F'. The velocity of the gas blast was maintained nearly constant. The value of the velocity was measured by a small open water manometer.

The apparatus for investigating the state of the gas issuing from the ionization chamber consisted of two parts: (1) the test cylinders, (2) the electrometer and its connections (see Fig. 2). The test cylinders of brass consisted of a concentric system of which the outside one A was closed at both ends by brass caps screwed on air-tight. It was 6.0 cm. long and had an inside diameter of 3.5 cm. The inner cylinder B was 5.0 cm. long and 2.0 cm. in diameter outside. The end nearer to the incoming gas was closed with a brass cap. A small brass tube C 0.4 cm. in diameter held B in place. The gas entered the system through the glass tube D which was placed opposite the annular space between A and B. The gas left the cylinders through the holes in the tube C. Thus the gas had to travel down between the cylinders, turn and pass up inside of B, turn again as it entered C, and pass along it for some 15 cm. before finally emerging past a thermometer. It thus seemed probable that even with a small potential gradient between the cylinders and a fairly rapid rate of flow of the gas, it would be possible to catch all of the ions before the gas escaped into the air. This assumption seems to have been justified by the actual performance of the apparatus. The tube C was insulated from A by the vulcanite plug P. A short piece of rubber hose covered with tin foil T connected C to the exit tube E. A stiff wire W_1 connected to C led through a grounded brass tube into the cabinet containing the electrometer and its connections. A similarly screened wire W_2 could be screwed to A, and by means of it A could be charged to any desired potential by a suitable storage battery. The entire cylinder system was enclosed in a large brass cylinder S, 10 cm. in diameter, which could be grounded and thus screen the testing apparatus from all outside influences. The Dolezalek electrometer after being properly adjusted, as described by Rutherford,[1] had a very slight normal leak, and could be made to have a sensitiveness of anything up to 7,500 scale divisions per volt P.D. between

[1]Radioactivity, 2d ed., p. 95.

the quadrants. The electrometer needle was suspended by a fine quartz fibre, and was charged from a water-battery by contact, usually to a potential of 40–100 volts. The electrometer was placed inside a cabinet lined with tin foil, and all contacts with it were made without opening the cabinet by means of levers operated by strings from the observer's seat. Either pair of quadrants could be connected (1) to the ground, (2) to a source of known E.M.F., (3) to the test cylinders. Deflections of the electrometer needle were read with a telescope and scale at a distance of about 2 meters. A standard cadmium cell of potential $V = 1.0177$ volts was used for calibrating the electrometer. On account of the sensitiveness of this instrument it was necessary to tap off a known fraction of the E.M.F., and suitable resistances were used in a simple potentiometer device to give one-eleventh the E.M.F. of the standard cell.

In using the apparatus it was desirable to know the pressure in the discharge tube which would produce the maximum effect in the ionization chamber. A preliminary experiment in which the pressure of air in the screen cell was kept at a low constant value (about .15 mm.), while the pressure of hydrogen in the tube was varied, showed a sharp increase in the effect up to a pressure of 1 mm. and a more gradual diminution from that point up to 10 mm. In all subsequent work, therefore, the pressure in the discharge tube was kept at an approximately constant pressure of 1 mm. This was also the pressure giving a maximum brilliancy when the tube was excited, though it did not correspond, as might have been expected, to the passage of maximum current through the tube, as was shown by measuring this current by means of Pierce's crystal rectifier. The maximum for the current took place at a pressure of 0.3 to 0.4 mm. To obtain constant results it was necessary that the tube should be excited for a constant short interval of time. A long excitation, by heating the tube, might set free occluded gases and thus change the pressure and therefore the tube's effectiveness. To this end a contact-maker was employed which illuminated the tube for one and one-fourth seconds. This instrument was tested for constancy of operation by connecting it to a chronograph. The greatest deviation from the mean of seven readings proved to be 2.25 per cent.

Another factor which it was necessary to make constant was the velocity with which the gas to be tested was blown through the ionization chamber. This was done by choosing arbitrarily a value on the water manometer which gave a deflection in the electrometer of the desired amount and then regulating the blast so that the manometer indicated this same reading each time an observation was made. The mean error of setting the blast repeatedly upon an arbitrarily chosen manometer reading was found to be about 2 per cent.

During an experiment it has been noticed repeatedly that apparently identical conditions gave rise to electrometer deflections which differed from one another by about five per cent. It seems that practically all of this may be accounted for by variations in the blast and length of exposure.

Manipulation.

Lyman[1] has found that the absorption of light in the Schumann region by oxygen is in the form of a band; and that, as the pressure increases, the absorption spreads much more rapidly toward the less refrangible side than in the other direction. For a column of gas 1 cm. thick at atmospheric pressure the band extends from λ1268 to λ1770, and for a pressure of .02 atmosphere from λ1350 to λ1500.

If oxygen is admitted to the screen cell at pressures varying from .0001 to 1 atmosphere, more and more of the effective rays from the discharge tube will be absorbed in passing through it. Thus the ionization produced in the chamber should be reduced with each increase of pressure in the screen cell. The wave-lengths which are available for the production of ionization in the chamber are those which get through the screen cell at any given pressure, and these may be determined when the width of the oxygen absorption band for the given pressure has been found.

The method of procedure in getting the relation between the two quantities—light entering the ionization chamber, and resultant ionization— is as follows: The pressure in the screen cell is reduced very low and measured on the McLeod gauge. A gas is allowed to

[1]Astroph. Journal, 27, p. 87, 1908

blow through the ionization chamber and test cylinders at the desired constant velocity as indicated by the water manometer. Before reaching the chamber the gas has to pass through 30 cm. of glass wool and over 25 cm. of calcium chloride and 25 cm. of phosphorus pentoxide. It is therefore assumed to be dust-free and dry. While one pair of quadrants in the electrometer is kept in connection with the earth, the other pair, connected with the inner of the test cylinders, is now insulated. The contact-maker is set in motion and allowed to excite the discharge tube once. Shortly after the illumination ceases the stream of gas is shut off, and the resulting deflection in the electrometer observed. Both pairs of quadrants, together with the inner test cylinder, are then connected to earth, and oxygen from the electrolytic generator carefully dried over phosphorus pentoxide is admitted to the screen cell changing the pressure therein by a desired amount, as indicated by the closed mercury manometer. The tube is again excited, the resulting deflection made, and so on.

Since, as has already been shown, the light of short wave-length entering the ionization chamber depends upon the pressure of oxygen in the screen cell, and since the electrometer deflections are very nearly proportional to the resulting ionization, curves have been obtained showing the relationship existing between these two quantities for different gases. None of the gases used produced measureable deflections when blown unilluminated by the discharge tube through the test cylinders.

OXYGEN.

Oxygen, 92 per cent. pure, made by the potassium chlorate black oxide of manganese process and put up in a cylinder under pressure, was passed through distilled water, then through two large U-tubes each arm of which contained 10 cm. of phosphorus pentoxide held in place by plugs of glass wool. These were supported vertically so that the oxygen was forced slowly through the phosphorus pentoxide, not over it. The gas was collected over mercury and finally blown through the ionization chamber. Glass tubing only was used for all connections. After passing the entrance to the water manometer the oxygen was again dried over phosphorus pen-

toxide before finally entering the chamber. With oxygen thus dried results were obtained which the curve showing pressures of oxygen in the screen cell, in centimeters of mercury, plotted against electrometer deflections is given in Fig. 3, *A*. Since

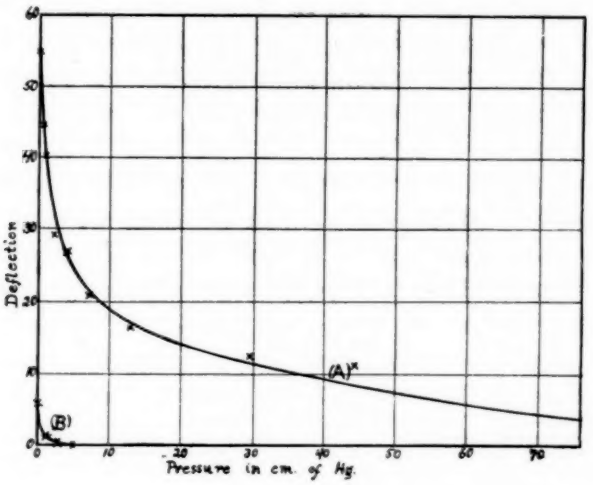


Fig. 3.

(*A*) Negative leak. Oxygen. (*B*) Negative leak. Hydrogen.

the outer of the test cylinders (*A*, Fig. 2) was charged to a potential $V = -20$ volts, this curve represents the negative leak between the two cylinders. A large proportion of the work has been done with the outer test cylinder at a constant potential $V = \pm 20$ volts. The saturation curves (not here shown) which have been obtained, show that for the gas velocities generally used this value of the potential was sufficient. The gas was at a temperature of 24° C., and its velocity through the ionization chamber was 20 cm./sec. The electrometer had a sensitiveness of 165 cm. per volt P.D. between the quadrants, and its capacity, together with that of the test cylinders and connections was 111 cm., or $111/9 \times 10^{-11}$ farads. Taking the maximum deflection in the above curve, it is easy to see that the insulated pair of quadrants has acquired a potential $V = 55/165$ volts, and, since $Q = VC$, $Q = 55/165 \times 111/9/\times/10^{-11}$, or 4.2×10^{-11} coulombs. If it is assumed that the average current may be obtained by dividing this quantity

by the time during which the gas is exposed to ultra-violet light, then

$$i = \frac{4.2 \times 10^{-11}}{1.25},$$

or the average current is 3.3×10^{-11} amperes. Considerably larger currents have been obtained. The normal rate of leak in the electrometer used in these experiments was 0.4 cm. per *minute*, and the maximum leak in the ionized gas was in this case at the average rate of 44 cm. per *second*.

An examination of curve *A* shows it to be made up of two parts: first, a nearly straight portion, rising slowly as the pressure in the screen cell is changed from 76 to about 19 cm. of mercury; second, a curved part, which rises rapidly as the pressure is reduced from this point down to the lowest value reached. An inspection of Lyman's paper[1] shows that, according to the evidence of the photographic plate, as the pressure in the absorbing cell is reduced from 76 to 19 cm., the width of the absorption band in oxygen becomes only slightly less, *i. e.*, changes from λ1770–1268 at 76 cm. to λ1740–1280 at 19 cm.; while from this point on the band rapidly becomes narrower with decreasing pressure, extending from λ1600 to λ1335 at a pressure of 4 cm., and disappearing entirely below a pressure of 1.5 cm. The absorption band is thus unsymmetrical, the change taking place more rapidly on the less refrangible side of the band. It, therefore, seems justifiable to assume in these experiments that, when the pressure of oxygen in the screen cell is about 19 cm. of mercury, two narrow bands of light pass through into the ionization chamber, in addition to all the light which went through at a pressure of 76 cm. These two bands extend from λ1770 to λ1740, and from λ1280 to λ1268. To them may be due the rise of curve *A*, which takes place slowly between the above pressures. Then, as the pressure in the screen cell is reduced to its lowest value, more and more of the wave-lengths in the Schumann region pass through into the ionization chamber. To these wave-lengths is due the rapid rise of curve *A*, which takes place at the lower pressures. It may be mentioned here that there is no reason to believe that the

[1] *Loc. cit.*

smallest amount of energy necessary to produce a chemical effect upon a photographic plate is the same as, or even comparable with the smallest amount necessary to produce ionization detectable by the method employed in this research. It is, therefore, quite probable that the sensitiveness of one method differs considerably from that of the other.

In consideration of these facts the author[1] has already stated that volume ionization is produced by light of wave-length less than λ1800, and that this effect increases with decrease in wave-length, at all events in the region between λ1850 and λ1400.

When the outer test cylinder was charged positively the results were, within experimental error, the same as those given above, showing that in the ionization chamber positive and negative ions are formed in equal numbers.

Hydrogen.

The gas was made electrolytically, passed through phosphorus pentoxide and collected over mercury in the same manner as the oxygen. In order to obtain deflections large enough to measure accurately the velocity of the gas stream was increased to 30 cm./sec., and the sensitiveness of the electrometer to 190 cm./volt. However, for the sake of comparison with the oxygen curve, the leak in hydrogen when the outer test cylinder was charged to a potential $V = -20$ volts has been plotted on Fig. 3 as curve B, and is on the same scale as curve A.

Nitrogen.

This gas was prepared by passing the nitrogen from a cylinder obtained from the Lindé Air Products Co. of New York through distilled water, over red hot copper, and through phosphorus pentoxide. It was collected in the same gasometer over mercury and used as were the other gases. The manner in which the gas in the cylinder is made by the company permits the presence of small quantities of argon and helium as impurities, but precludes the possibility of carbon dioxide or monoxide. A specimen of this gas analyzed for traces of oxygen and oxides of nitrogen showed:

[1]Nature, 77, p. 582, 1908.

"Oxygen 0.4 per cent., oxides of nitrogen 0.02 per cent. This does not include nitrous oxide or nitrous anhydride. The presence of the latter is, however, almost impossible, and of the former very unlikely." The results obtained with this nitrogen are plotted in Fig. 4. This curve represents the negative leak, since the potential of the outer test cylinder was -20 volts. Moreover, the gas velocity through the ionization chamber was only 11.5 cm./sec., and the electrometer had a sensitiveness of 75 cm./volt, which corresponds to a capacity of 70 cm.

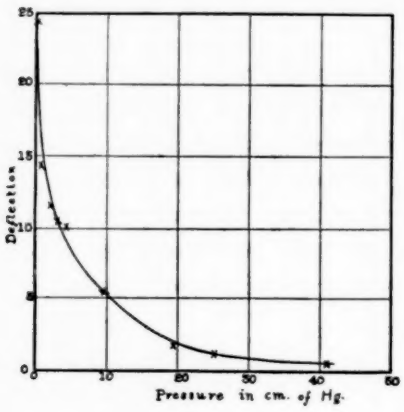


Fig. 4.
Negative leak. Nitrogen.

Nitrogen was also made from potassium nitrite by Gibbs's method. A specimen of this gas which was analyzed gave: "Oxygen none, oxides of nitrogen none." The steep rise of the ionization curve for pressures less than 2 cm. was even greater in this case, which indicates that the sharp rise is not due to the impurity of the gas.

AIR.

Air from the laboratory was passed through distilled water, and then through the same tubes of phosphorus pentoxide, being collected as before in the mercury gasometer. The results obtained for the negative leak are shown by the curve in Fig. 5. The conditions of this experiment were similar to those for the other gases, though it is not possible to compare the magnitudes of the curves given thus far, owing to differences in gas velocity and sensitiveness of the electrometer.

COMPARISON.

It has frequently been shown that absorption and ionization in a gas go hand in hand. Therefore since it is known that air and oxygen absorb light of extremely short wave-length very strongly,

while nitrogen is much more transparent and hydrogen hardly absorbs at all, it was to be expected that ionization would be detected in air and in oxygen, but that in nitrogen and in hydrogen, the amount of ionization, if it could be detected at all,

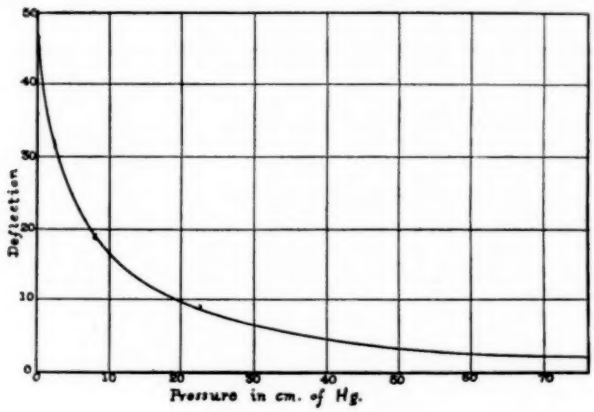


Fig. 5.
Negative leak. Air.

would be extremely small. In Fig. 6 are given the ionization curves obtained all in a single day, and under as nearly the same conditions as possible. The gas velocity was less than that of any of the previous curves and was the same for all. The potential of the outer test cylinder was $V = -16$; and the electrometer had a sensitiveness of 170 cm./volt. Under these conditions the ionization in hydrogen, even when the gas velocity was doubled, was so small as to be unmeasurable.

An inspection of the curves indicates that while air and oxygen show marked ionization, and hydrogen practically none, the ionization which takes place in nitrogen is unexpectedly large, and increases greatly for pressures in the screen cell less than 1 cm. Moreover, since a given thickness of air is more transparent than the same thickness of oxygen, it might be expected that the air curve of ionization would be lower than that for oxygen, but the opposite has always been found to be the case. It may be possible that small amounts of ozone, carbon dioxide, and carbon monoxide, present in the air account for a small portion of the ionization de-

tected, but it seems as if much more of it might be due to nitrogen than had previously been supposed possible.

In all four gases there is unmistakable evidence of a sharp rise in the ionization curve when the pressure of oxygen in the screen cell is reduced below 2 cm. Since it was earlier shown that the shortest

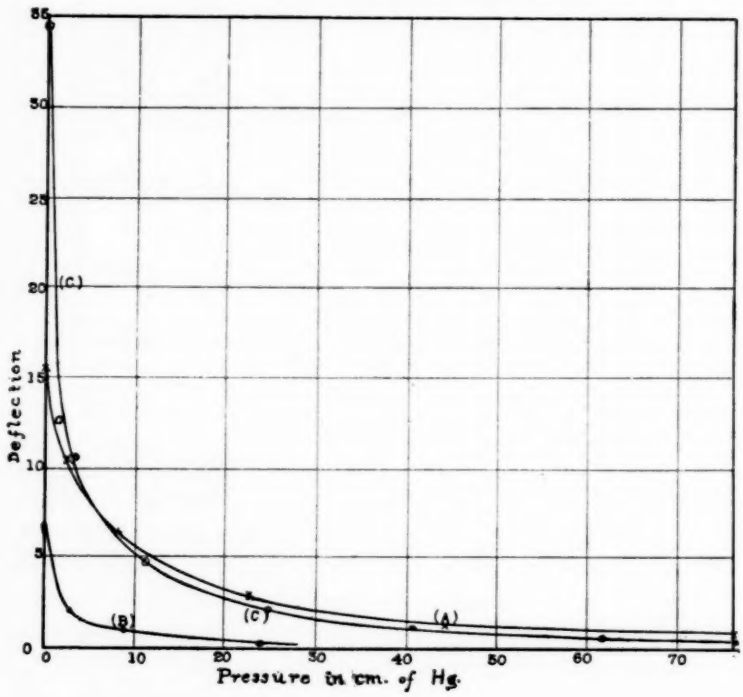


Fig. 6.
Negative leak.

wave-lengths passed through the screen cell only when the pressure in it was as low as 2.5 cm., the above result indicates that ionization increases very greatly as the wave-length decreases, at all events in the region between λ1850 and λ1400.

Although Lyman[1] has found that the absorption of ultra-violet light by nitrogen is small and increases regularly with decreasing wave-length, Schumann[2] states that nitrogen absorbs particular wave-lengths very energetically. It is known that nitrogen absorbs

[1] *Loc. cit.*
[2] *Loc. cit.*

wave-lengths between λ1500 and λ1300, such as pass through the screen cell at the lowest pressures, and if the absorption is particularly energetic in this region it may account for the observed rise in the ionization curve.

Dust.

The work of E. Bloch[1] seems to show that minute particles held in suspension by a gas, when acted upon by ultra-violet light, may produce a photo-electric effect which simulates that of volume ionization. In order to show that the results obtained in these experiments were not due to such a photo-electric effect, a plug of cotton wool 15 cm. long was inserted in the gas blast in addition to the many plugs of glass wool already there. The insertion of the cotton wool produced no detectable effect. It is also to be observed that the ionization in hydrogen is extremely small, yet from the manner of its production, there might be as much dust in hydrogen as in the other gases.

Water Vapor.

If water vapor has any effect, it is of great importance in this work, since it might produce absorption in the oxygen of the screen cell, resulting in a *smaller* electrometer deflection than if the oxygen were dry; or it might produce ionization in the gas being tested, resulting in a *larger* deflection. The following experiments will show that water vapor not only has an effect both in the screen cell and in the ionization chamber, but also that this effect is most pronounced.

Curve *A*, Fig. 7, is the same curve previously shown as *A*, Fig. 3, and represents the negative leak in oxygen when both the oxygen in the screen cell and the oxygen in the ionization chamber are dry. If the oxygen in the screen cell is kept dry, while oxygen which is slightly damp is taken from the previously mentioned oxygen cylinder, and passed through the ionization chamber, the result is curve *B* which falls much less rapidly at low pressure than *A* and does not reach it until the pressure in the screen cell has risen to 54 cm. of mercury. If this same undried oxygen from the cylinder is used in the screen cell as well as in the ionization chamber, the result is curve *C*, which is distinctly lower than *B* even up to atmospheric

[1] *Loc. cit.*

pressure, with the exception of the region below a pressure of 2 cm. of mercury. It was not convenient to saturate the oxygen which was admitted to the screen cell with moisture; so, instead, upon one occasion when the air in the laboratory was exceedingly damp it

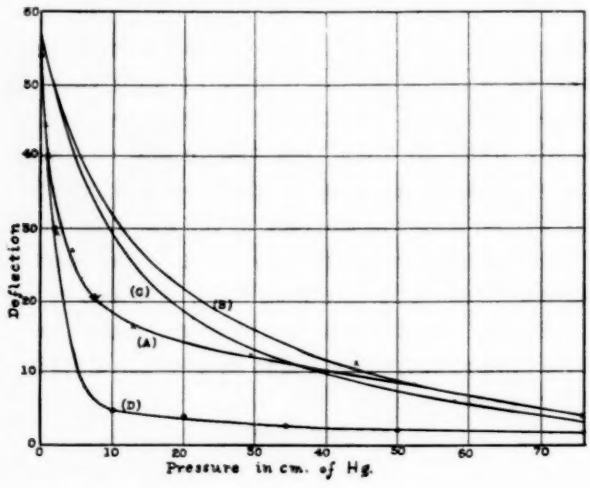


Fig. 7.
Effect of water vapor.

was admitted directly to the cell, while slightly damp oxygen from the cylinder was passed through the ionization chamber. The resulting state of affairs is shown in curve *D* and is conclusive in regard to the possibility of absorption due to water vapor in the screen cell.

MERCURY VAPOR.

W. Steubing[1] has found that mercury vapor is ionized by light in the region of λ1800–2400 It is possible that it may be ionized also by light in the region of λ1250–1800. If so, since all of the gases examined were collected over mercury, and since the screen cell was in continuous connection with a mercury manometer, it might be possible for mercury vapor to play a part in the phenomena here under investigation. However, since the vapor pressure of mercury is so small at atmospheric pressure, it is not likely that such minute quantities of this vapor as could mix with the gas

[1]J. Stark, Phys. Zeitsch., 10, 18, p. 623.

under investigation in the gasometer would affect the amount of ionization observed, even if the vapor were capable of producing any effect at all. No effect ascribable to mercury vapor in the ionized gas has been detected in these experiments.

Since the oxygen admitted to the screen cell is subjected to pressures all the way from atmospheric down to .01 mm. of mercury, it might very well be the case that at the lowest pressures used mercury vapor might constitute nearly one per cent. of the gas in the cell, and might produce a much greater percentage of absorption. Evidence of such an effect has been observed with all the gases examined at very low pressures of oxygen in the screen cell; but this is especially noticeable with nitrogen, since such a large proportion of the observed ionization in this gas is produced with low pressures in the screen cell.

Chemical Changes.

Many investigators have shown that ordinary ultra-violet light changes oxygen into ozone, and Lyman[1] has found that the light of extremely short wave-length used in this work does so to a very marked degree. It is therefore undoubtedly true that some of the oxygen used in the screen cell in these experiments is turned into ozone. However, since it has also been shown[1] that the absorption due to ozone does not differ appreciably from that due to oxygen this fact alone should not be a source of error here; unless, indeed, the method of ionization should prove to be superior to the photographic plate as a detector of absorption. If, on the other hand, the ozone when formed produces or facilitates other chemical changes, it might be possible that the resulting products of such changes would form a very considerable source of error.

Two effects have been observed which might be accounted for on the assumption that the ozone facilitates the formation of a layer of gas very close to the fluorite window, like that described by Hallwachs[2] in his explanation of photo-electric fatigue. One of the observed effects is the falling off of deflections in the electrometer taken successively under apparently the same conditions, when

[1] *Loc. cit.*

[2] Phys. Zeitsch., 21, p. 766, 1906.

the pressure of oxygen in the screen cell is anything from 1 to .0002 atmosphere. This effect is very similar to that ascribed to the presence of mercury vapor, but differs from it in that the deflection can be brought up to its initial maximum value either by waiting for ten minutes between readings, or by admitting fresh oxygen and reëxhausting to the same pressure as before. The first operation might give the ozone time to break up into oxygen, and the gas layer to become dissipated; while the second might be effective through breaking up of the gas layer by the inrush of fresh gas, followed by the loss of some of the ozone by reëxhaustion as well as by the natural process of breaking up into oxygen.

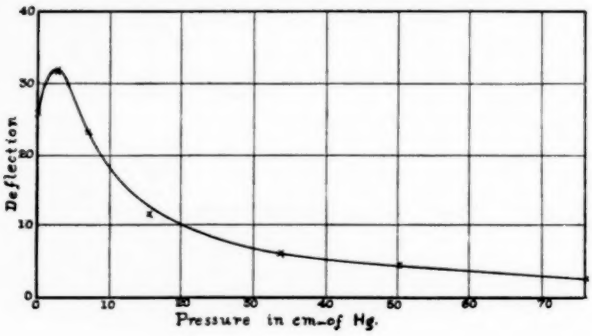


Fig. 8.

Effect of chemical action on fluorite.

The other effect has been observed not infrequently after the apparatus, as shown in Fig. 1, has been in use for some time. It consists of a complete change in the character of both positive and negative ionization curves for pressures less than 2.5 cm. of mercury in the screen cell. Instead of increasing as the pressure in the cell is reduced to its lowest value the curve passes through a maximum at a pressure of about 2 cm., falling off sometimes to only 80 per cent. of its maximum value when the lowest pressures are reached. Fig. 8 represents such a case when $V = -20$ volts and the ionized gas was oxygen. Upon taking apart the apparatus no film was found on the side of the fluorite window F (Fig. 1) next the discharge tube, where one might have been formed from a metallic deposit from the aluminum electrodes; but a film was formed on

the side of the window F next the screen cell. No film has ever been found on the window F' (Fig. 1). The film has always been observed whenever the character of the ionization curve has undergone change, as in Fig. 8. Upon one occasion when the film was carefully examined, it was found to consist of two distinct parts; one was composed of fine, white, microscopic dust, which could be brushed off easily by a touch from some cotton wool; the other, when viewed in reflected light, appeared like a very thin film of whitish metal, which could be removed only after soaking in alcohol, and then rubbing briskly with cotton wool. The layer of dust occupied the exact central portion of the window and was in the form of a disc of diameter very little larger than the end of the capillary in the discharge tube, exactly opposite to which it was situated. The other film was also circular in shape, though its outline was not so clearly defined as that of the disc of dust, and its diameter was about three times as great, the two being concentric. On one side a notch in the circumference of the outer film was noted where no deposit existed. In this instance the fluorite window was 2.5 mm. thick, and a close examination showed a flaw on the side next the discharge tube which proved to be in a straight line from the end of the capillary to the notch noted above, thus indicating that the flaw had cast a shadow, in the line of which no chemical action on the fluorite had taken place. This shows that the action must take place extremely close to the window; that the dust layer must be formed by the more intense light which shines down some length of the capillary; and that the larger film must be produced by the weaker illumination which comes from close to the end of the capillary. Furthermore, since no effect has ever been found on the window F', it shows that the effective rays here are the very shortest. When carefully dried oxygen is used in the screen cell the apparatus may run for weeks without the formation of the film; but if oxygen from the storage cylinder is used, or if air is admitted from the room even if partially dried, the film forms quite quickly, sometimes in a day. The formation of the film, then, seems to be due to the action on the fluorite of ozone in the presence of a small amount of water vapor. This suggests that hydrogen peroxide may be the effective agent.

Since the curves shown represent the ionization produced by the sum total of all the light passing through the screen cell at any given pressure, it is not easy to see how a maximum in such a curve could be produced. It is probable that the dust layer described above plays a double role in this process: (1) absorbing much of the light of shortest wave-length, (2) facilitating the formation of a gas layer on the fluorite by presenting a roughened instead of a smooth surface. If it is assumed that this gas layer forms more readily on the roughened surface at low pressures, or that its absorption is abnormally large for such pressures, and that it absorbs the shorter wave-lengths more easily than pure oxygen, it can be seen how starting with a very low pressure in the cell practically all the absorption taking place would be due to the dust film and to the gas layer; but if a little more oxygen were admitted to the cell the gas layer might be disturbed, while the absorption due to the oxygen itself would increase.

If the increase in absorption due to the introduction of the oxygen was not as great as the gain in transparency due to the breaking up of the gas layer, the curve of ionization would rise. As more oxygen was admitted, the increased absorption due to the oxygen would overbalance the decrease due to the change in the gas layer, and therefore the ionization curve would begin to fall again, and would continue to do so up to atmospheric pressure.

It is possible that the effect here described is the same as that noted by C. T. R. Wilson[1] in his experiments on the formation of clouds by ultra-violet light. He has suggested that the formation of hydrogen peroxide by ultra-violet light would explain the phenomena observed by him. Although his source of illumination (zinc spark in air) gave rise to no such extremely short wave-lengths as those effective here, nevertheless it was a much more intense source than the hydrogen tube of these experiments, and might have produced hydrogen peroxide on that account. Lenard[2] has also found that ultra-violet light produces cloud nuclei which are non-electric in character, though he has not suggested what their real nature might be. It is quite possible that these, too, may be minute

[1]Phil. Trans., 192, p. 403, 1899.
[2]Ann. Phys., 3, p. 298, 1900.

particles of hydrogen peroxide. It may be also that the roughening of a surface under the action of ultra-violet light noted by many investigators is due to the same cause as that which produced the dust layer described above.

Whatever may be the explanation of the phenomenon, it is certain that the maximum in the ionization curve exists only when the film on the fluorite window is present.

Temperature.

The gases examined were all at nearly the same temperature, that is from 15° C. to 25° C. Between these limits there was no detectable temperature effect.

Conclusions.

In conclusion it should be noted that the objection raised by Bloch to Lenard's work (dust) does not apply to the present investigation, since the insertion of a long plug of cotton wool in the gas stream was without effect. Furthermore, since it has been shown that the ionization produced in hydrogen is *extremely* small, this fact proves conclusively that the results obtained were not due to photo-electric action at the inner surface of the ionization chamber. This point meets the objection recently raised by Stark.

Finally, although the hydrogen tube used emitted light of low intensity, it was possible to obtain rather large currents through air, oxygen and nitrogen, owing to the great power of ionization possessed by the very short wave-lengths. Therefore, it seems clear that the reason why J. J. Thomson and McKaye, and others have obtained only extremely small currents in oxygen is because they have not employed a source of illumination emitting light of sufficiently short wave-lengths. The large currents measured by Stark were obtained in vapors having a very complex molecular structure, and not in oxygen. During the course of the present investigation it was found that, if alcohol or ether vapor were mixed with the gas under examination, the electrometer deflection in one second was so large as to be unmeasurable. This shows that for vapors of complex molecular structure the shortest wave-lengths also are capable of producing very large currents.

SUMMARY.

1. Using a discharge tube filled with hydrogen as a source of light and a screen cell filled with oxygen at various pressures, ionization curves have been obtained in air, oxygen, hydrogen and nitrogen.

2. The ionization in air, oxygen and nitrogen is considerable. That in hydrogen is exceedingly small. The currents obtained for all gases are large compared with the values of most other observers.

3. The power of ionization increases greatly with decrease in wave-length of light, at all events in the region below λ1850.

I take this opportunity of thanking Professor G. P. Baxter for valuable suggestions as to the production of pure nitrogen and also for superintending the analysis of the specimens of that gas.

The investigation was carried on in the Jefferson Physical Laboratory at Harvard University.

HAVERFORD COLLEGE, HAVERFORD, PA.,
May, 1910.

A METHOD FOR THE QUANTITATIVE ANALYSIS OF MUSICAL TONE.

By Preston Hampton Edwards.

I. Introductory.

THE present investigation was undertaken with the purpose of making an analysis of the musical tones actually emitted from a violin or other musical instrument. The problem of the quality of tones has engaged the attention of many investigators, yet no systematic quantitative results have been obtained. Helmholtz[1] did a great deal in the analysis of tones, both from consideration of the method of their production, as in the case of the vibration of a violin string and that of the air used in an organ pipe; and by his resonators, which gave an indication of what was actually going on in the air. Koenig[2] attacked the problem with resonators and manometric flames, while Scripture[3] studied enlarged phonograph records. Dayton Miller[4] has recently used an improved oscillograph method.

As has been said, none of these methods has as yet furnished quantitative results, and they can hardly be expected to do so unless greatly improved in the future. The use of resonators by Helmholtz and Koenig depends on the human ear in one case and on manometric flames in the second, and either can only give qualitative results. The other methods are dependent on the analysis of irregular curves, which is a difficult and not always certain process. There is also in many cases the complication introduced by the membrane or other parts of the recording device having free periods of their own. So the first step of this work was to look for a better method of analysis.

[1]Tonempfindungen, Abs. 3, 4, 5.
[2]Expériences d'Acoustique, p. 70 ff.
[3]Elements of Experimental Phonetics.
[4]Reported at Baltimore meeting of A. A. A. S., Dec., 1908.

II. THE METHOD.

The first device tried was one used by M. Wien,[1] who cut away a portion of the wall of a Helmholtz resonator and replaced it by a metallic diaphragm tuned to the tone of the resonator. The vibrations of this diaphragm were communicated by a stylus to a light steel spring extending over the diaphragm from a support at the side, and on the end of the spring was mounted a small mirror forming an image of a slit on a screen, to indicate the amplitude of the vibrations. In my tests a cylindrical resonator was used, with the usual small orifice at one end, while at the other end was a larger opening, over which membranes of various sorts could be placed and held fast by a flat brass ring screwed on. It was soon found, however, that the system formed by the coupling of these two units, instead of having a single response, answered to two notes several tones apart, even though the two were tuned to the same frequency before coupling. This fact makes its indications doubtful, thus rendering it useless for the purposes of this investigation. Following this some tests were made with Rayleigh's disk,[2] which finally led to the adoption of a system composed of a mica disk hung close in front of the opening of a resonator, at an angle of 45° with the plane of the opening.

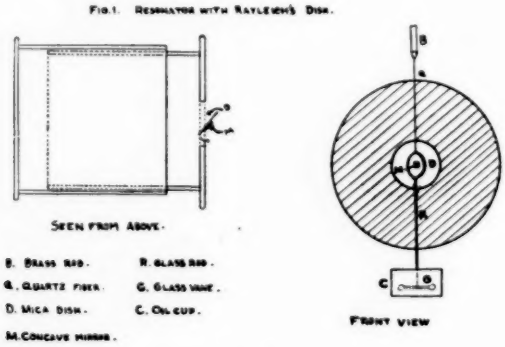


Fig. 1.

The arrangement of this system may be readily understood from the accompanying sketches (Fig. 1). The disks were made of mica,

[1] Wiedemann's Annalen, 36, p. 835, 1889.
[2] Rayleigh, Theory of Sound, II., p. 44.

on account of its lightness and ease of handling. The circles were cut out with a pair of bow dividers with sharpened points. The concave mirrors were made by silvering, or better, platinizing the surface of a concave eyeglass lens such as can be obtained from opticians, having by reflection a focal length of about 50 cm. After silvering the lens it was cut into strips and chips struck off from the surface by hitting the edge with a hammer. Mirrors can be made in this way of 1 milligram or less in weight, which will give a good image of a Nernst filament at one meter's distance. The quartz fiber could be made of any fineness, according to sensibility desired. At the bottom of the disk was attached a fine glass rod, and at the lower end of this was a little glass dumbbell hanging in a cup of kerosene for damping. The motion of air in and out of the mouth of the resonator when it is "speaking," exerts a couple on the disk, tending to set it in the plane of the opening, and the deflection of the image thrown by the mirror on a screen measures the angle through which it turns.

The cylindrical form of resonator made of two pieces of telescoping brass tubing was chosen on account of ease of tuning. The larger ones were made by Koenig, of Paris, and were kindly put at my disposal by the psychological laboratory of this university. In use the nipples made for insertion in the ear were closed with small corks. The smaller ones were made in the workshop of this laboratory, and had no nipples (see Fig. 1).

A series of 17 resonators was set up in this manner, for the analysis of the tones g and c′. (In this paper Helmholtz's designations will be used for the notes, and the partials will be designated by their relative frequency numbers, *i. e.*, the fundamental will be called the first partial, the octave the second, etc.) The whole set up comprised the following:

Partials of g.	Partials of c′.
1. g	1. c′
2. g′	2. c″
3. d″	* 3. g″
* 4. g″	* 4. c‴
5. b″	5. e‴
6. d‴	* 6. g‴
* 8. g‴	7. bb‴ (app.)
*12. d^{IV}	8. c^{IV}

Partials of g.	Partials of c'.
*16. g^{IV}	* 9. d^{IV}
	10. e^{IV}
	*12. g^{IV}
	16. c^{V}

Those resonators marked with a star were common to the two sets. The whole set was placed on a table and covered by a box of light paper pasted on a skeleton frame, with a window in front made of very thin, transparent celluloid. The object of this cover was to protect from air currents while allowing free passage for sound. The resonators were inclined to the front of the box so as to allow the disks to face the source of light and the screen, both of which were placed at about a meter's distance in front of the array of resonators. The source of light was a Nernst glower and the screen was made of tracing paper stretched on a wooden frame. Its dimensions were about 40 by 75 cm.

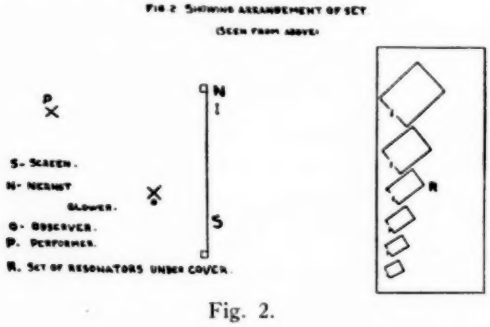


Fig. 2.

As one of the leading objects of this paper is to establish the value of this method of sound analysis, it will be advisable to discuss the qualities which differentiate it from other methods and contribute to, or limit, its usefulness.

III. FEATURES OF THE METHOD.

1. *Sensibility.*—This is one of the most valuable features of the method. Systems set up without unusual care showed deflections of several millimeters for the gentlest possible sound of the voice of the observer, or for a piccolo blown softly at the far end of a neighboring large room. Naturally the sensibility of a system depends on the following:

(*a*) *Multiplying Factor of the Resonator*, which has been shown by Helmholtz to be expressed by the formula $dp/dP = \sqrt{2R^3/\pi^2 S}$ (see page 29).

This gives a comparatively low value for the resonators corresponding to the higher partials, since their openings are in general larger in comparison to their volumes than for the lower resonators.

(*b*) *Size and Length of the Quartz Fiber.*—We can always increase the sensibility in this direction, at the expense of stability and ease of handling. A proper balance between these two desiderata must be found for any one investigation; in the present work no attempt was made to push the sensibility to extreme values.

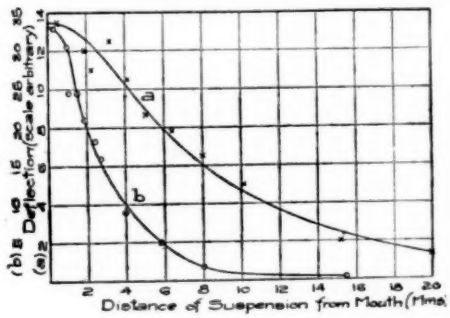


Fig. 3.

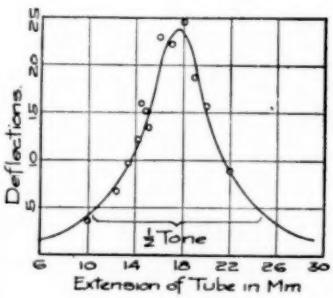


Fig. 4.

(*c*) *Size of the Disk.*—Lord Rayleigh's formula for the couple is: $M = \frac{4}{3}\rho a^3 W^2 \sin 2\theta$ (where a = radius of disk, W = mean velocity of vibrating particles, ρ = density of air, and θ = inclination of disk to plane of mouth), which shows that the effect can be increased by increasing the diameter of the disk, in proportion to the cube of this diameter. The size of the disk, however, must be kept well under the size of the resonator's mouth. It was thought that the presence of the disk might have the same effect as reducing the size of the mouth, *i. e.*, might lower the pitch of the resonator, but a test with several persons of good musical ear did not indicate such an effect in the slightest degree.

(*d*) *Distance of Suspension from Plane of the Mouth.*—In Fig. 3 are shown curves between these distances and the deflections produced by a constant source of sound (an organ pipe blown at uniform pressure). This would afford an easy way of varying the sensibility

if so desired. In this work the distance was kept constant, and as small as practicable (about 1 mm.).

2. *Selectiveness.*—Fig. 4 shows a curve of deflection obtained when the tuning was varied by drawing out or forcing together the two telescoping tubes forming the resonator, the source of sound being kept constant. The extension corresponding to a semitone change of pitch is indicated in the figure. Quite similar curves were obtained when the source of sound was tuned (*e. g.*, an organ pipe tuned by turning down a portion of the top margin, and compared

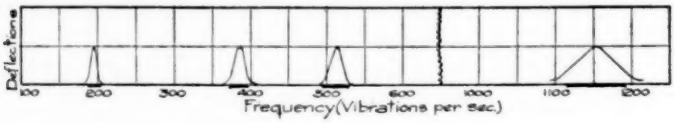


Fig. 5.

by beats with a tuning fork). In Fig. 5 four of these curves are plotted on a line of abscissas which represents total frequencies. The heavy line beneath each curve indicates a range of a semitone. This sketch shows us that neighboring harmonics will not interfere until we reach the neighborhood of the sixteenth, where they are about a semitone apart. It will be noticed that the g′ and d‴ resonators, which were cylindrical, were less selective than the g and c″, which were of the Helmholtz pattern. Whether this is due to their cylindrical shape, or to some relation between volume and size of mouth, has not yet been investigated.

3. *Damping.*—It was found possible by the arrangement of a glass rod dipping in oil as shown in Fig. 1, to make the vibrations of the disk practically dead beat, so that in a fraction of a second the image on the scale, on the sounding of its tone, will move to a position which will be steady so long as the pitch and intensity are constant. Of any variation in either, however, it is a very delicate indicator, and it often warns the observer that a note sung is not holding to its pitch when his ear does not notice the fact.

4. *Indications.*—It will be noticed from the formula for Rayleigh's disk, that so long as the deflections are small, *i. e.*, θ very near 45°, the turning couple, and therefore the deflection, is proportional to the kinetic energy of vibration of the air at the resonator's mouth.

If therefore we know the "multiplying factor" of each resonator and the moment of torsion of each suspension, we can pass at once to the absolute energy belonging to each partial, in the open air. It seems more to the point to describe the quality of a tone by the energy of its components than by their amplitudes, and in the graphical representations of tone quality in this paper, the strength of each partial will be indicated by ordinates proportional to its energy of vibration, obtained immediately from the deflection of the corresponding disk, by the use of the two constants just mentioned. Helmholtz's formula for the multiplying factor of a resonator is

$$dp/dP = \sqrt{2R^3/\pi^2 S},$$

where dp represents the variation of pressure in the outer air, dP that in the resonator, R = radius of mouth, S = volume of resonator. Where we have to do with energy values, however, we must use the square of this ratio. Wien[1] experimentally found values in the neighborhood of 30 per cent. below the theoretical values as given by the above formula. His method however is not one which may be considered as accurate, and it is highly desirable that some means be found of experimentally arriving at a value of this ratio. Much time and effort were expended in this direction in connection with the present work, but no results worth recording were obtained. The writer hopes to continue these experiments in the near future. Meanwhile the theoretical value will be used in this paper.

To find the reducing factor for the suspended system, a system similar to those in use with the resonators, was suspended in a vacuum and its period observed. It was then removed and a piece of copper wire about as long as the diameter of the disk, was attached, by a bit of wax, along a horizontal diameter of the disk. The period was again observed in a vacuum, and since the moment of inertia of the piece of wire could be calculated, the moment of torsion of the quartz fiber was thus found. Each suspension was then directly compared with this standard by suspending the two successively in front of the same resonator and taking deflection produced when the note of the resonator was sounded by an organ

[1] M. Wien, *l. c.*

pipe at a definite air pressure. This comparison gives a factor by means of which the deflection of any suspension may be at once reduced to the equivalent deflection of the standard. Multiplying this deflection by its known moment of torsion gives M in the formula

$$M = \tfrac{4}{3}\rho a^3 W^2 \sin 2\theta.$$

Measuring a, the radius of the standard disk, and taking sin $2\theta = 1$, since θ does not vary much from 45°, the deflections being generally small, we have a means of calculating $\frac{1}{2}\rho W^2$, the mean kinetic energy per c.c. of the vibrating air at the resonator's mouth, and multiplying this by the factor $2R^3/\pi^2 S$ we find the mean kinetic energy per c.c. in the air, belonging to the corresponding partial. For the present purpose the deflections were reduced to the equivalent deflections of the standard and then multiplied by the factor $2R^3/\pi^2 S$, thus giving quantities *proportional* to the energy of the various partials.

It would be interesting to use this method to compare the total input and output of energy for various musical instruments, thus giving their efficiency as sound producers. Webster[1] has arrived at values of this efficiency, using only a single partial (the fundamental). The present work indicates that for many instruments his value would be very largely increased by taking account of all the partials.

IV. Room Used for the Tests.

In the preliminary trials it was found that the quality of a tone might vary greatly as the instrument producing it was moved about the room. This effect is doubtless due to standing waves produced by reflection from the walls of the room, and depends on the position of the source and of the receiver, and on the wave-lengths of the sound. The difference of wave-length of the different partials causes some to be weakened by interference at certain points, while others are strengthened, and so on. The curves in Fig. 6 show the effect on the relative strength of the first three partials of a c′ reed pipe, when the pipe was moved perpendicularly away from the

[1]A. G. Webster, On the Mechanical Efficiency of the Production of Sound, Leipzig, 1904.

wall of the room, its height from the floor being kept constant. The room was an octagonal one about 4.5 meters across. The resonators were near the opposite wall of the room. It is interesting to note that the maxima (or minima) of the first and third partials are found at points separated by distances nearly equal to their respective wave-lengths (for first partial $\lambda = 130$ cm., for third,

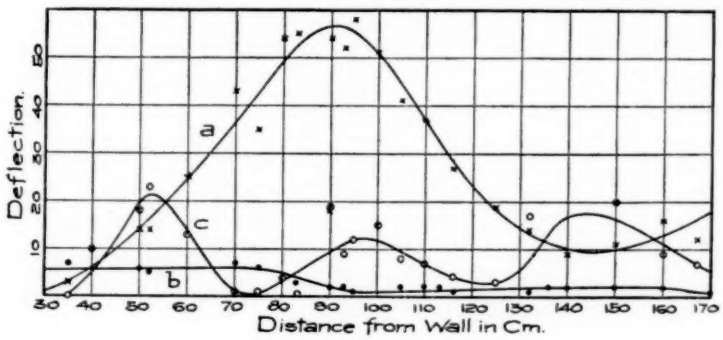


Fig. 6.

$\lambda = 43$ cm.). It would be easier to explain this if the distance were $\frac{1}{2}\lambda$. The second partial does not show any such marked effect as the other two.

In order to eliminate complications arising from this effect, a space was curtained off by burlap lined with cotton batting, forming a chamber about 10 feet by 6 feet by 7 feet, in one end of which was placed on a table the set of resonators protected by the paper covered box. The performer with his instrument stood at the other end of this chamber. The floor, as well as the sides and top, was covered with cotton batting about an inch thick. It is probable that even with all the precautions taken there were still complications present due to shadows and reflections, since the observer and the screen were between the performer and the resonators, and the table and other solid articles offered a considerable area of reflecting surface. In the more extended experiments which it is hoped will follow, a larger room must be prepared in which the observer and screen may be to one side, and solid materials reduced to a minimum. The table, for instance, might be made of slender steel rods with a top made of iron gauze. It would be advantageous to carry on

experiments in an open space out of doors, if such were available where the air would be sufficiently still.

V. Taking the Observations.

The manner of doing this was the simplest possible. The suspensions were so adjusted that each mirror threw an image of a Nernst glower on a screen, and the observer sitting in front of the screen soon became familiar with the position of the image corresponding to each partial. The performer stood behind the observer and produced a given tone half a dozen or a dozen times while

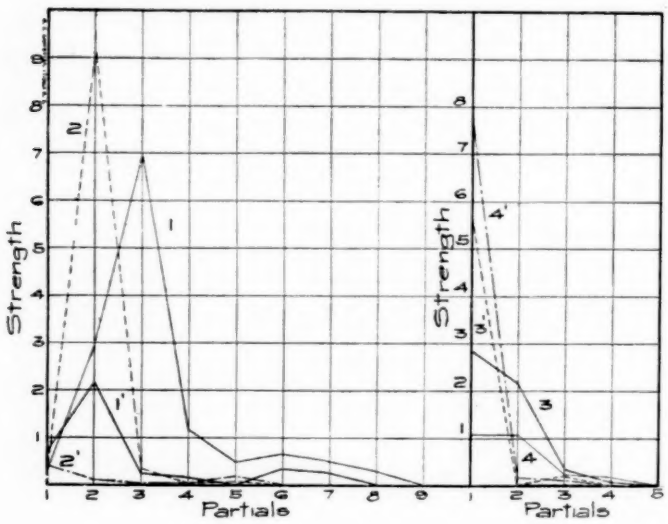


Fig. 7.

the latter noted the deflections of the images. There were often differences of as much as 100 per cent. in the deflections of the same image for successive productions of the same note, so an average value was taken. The following set of readings is given as an illustration. The column of readings headed by *m* under each tone was taken with the violin muted with a metal mute. An asterisk (*) indicates that there was no resonator to respond to that partial.

The figures must be modified as explained under III., 4, to show the actual proportions of the total energy of the tone, furnished

by the several components. This has been done to obtain the ordinates used in Fig. 7. It must be borne in mind that in this and similar graphical representations of tone quality only the ordinates have a meaning, the lines joining the summits of these ordinates being merely a means of showing that these ordinates belong to the same tone, in a way to appeal easily to the eye.

Record of P. H. E.'s Violin, played by A. H. P.

Partials.	Open g.		c'		g' Harmonic.		g' on d' String.		c''		g''	
		m		m		m		m		m		m
1.	.4	1.0	.7	2.0	6.5	13.0	2.5	18.0	30.0	.9	6.9	3.0
2.	3.4	2.5	24.0	.3	3.0	.0	1.5	.2	.8	.4	.3	.5
3.	9.0	.3	2.5	.2	.3	.2	.2	.1	.2	.0	.0	.0
4.	.8	.1	.2	.1	.1	.0	.2	.0	.5	.0	.0	.0
5.	.8	.0	.2	.5	*				.0	.0		
6.	.3	.2	.2	.0	.0	.0	.0	.0	.0	.0		
7.	.2	.1	.0	.0	*				*			
8.	.2	.0	.0	.0	.0	.0	.0	.0	.0	.0		
12.	.0	.0	.0	.0					*			
16.	.0	.0	.0	.0								

A more refined method of taking the observations would be, by means of auxiliary mirrors, to bring all the images into one vertical line, also to so adjust the sensibility of the systems that their deflections would all bear the same proportion to the energy of the corresponding partial in the open air. Then a film could be exposed while the tone was sounding and while not sounding, and the displacements of the images would give a picture of the instantaneous quality of the tone.

VI. Discussion of the Results.

The readings given in the table above, and (in part) represented graphically in Fig. 7, bring out at once two remarkable and important facts, (1) that the lower tones of the violin are extremely weak in fundamental, a very large proportion of the energy being contained in the overtones, and (2) that the effect of muting these tones is to increase, not only relatively but absolutely, the strength of the fundamental, while damping the upper partials. Muting the higher tones diminishes all of the partials together.

Fig. 8 shows the effect of different manners of bowing, in a somewhat exaggerated way. Record (1) is from a good English-made Amati model, about 150 years old, bowed by a good violinist to bring out its best effect; (1′) is from the same violin bowed with great force by another performer, to bring out its full power. It will be noted that while all the partials are increased in intensity by the stronger bowing, some higher ones are brought out which were not before present in measurable amount. Records (2) and (2′) are similarly taken from a somewhat "scratchy" violin of not very powerful tone, age and make unknown. The same sort of effect from strong bowing is shown as in the first case. It is interesting to note that among the differences introduced by different bowing, the individuality of each instrument still appears very clearly.

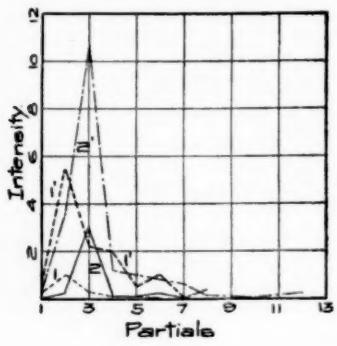


Fig. 8.

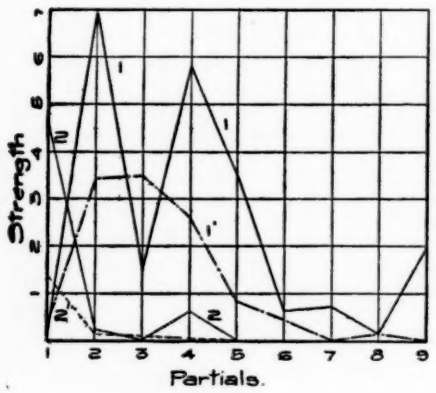


Fig. 9.

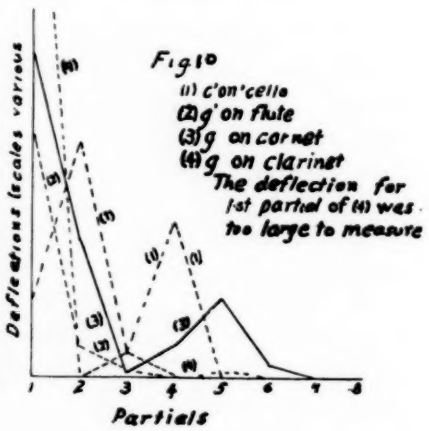


Fig. 10.

Fig. 9 shows the effect of varnishing. Through the kindness of Mr. Della Torre of this city a violin was obtained and strung "in the white," *i. e.*, without any varnishing at all. After making a record with it thus, he applied a varnish of his own and another record was taken.[1]

The three modifications of tone just mentioned, *i. e.*, muting, difference of bowing, and varnishing, are the only ones yet sufficiently tested to be reported on. It is hoped that the test may be continued long enough to get valuable data as to the effects of various other factors which easily suggest themselves, such as setting of sound post, position, shape and height of bridge, graduation of back and belly, etc.

Fig. 10 shows records of several other instruments which need not be here discussed. Each one of these instruments, however, ought to be studied in the same complete way as has been suggested for the violin.

VII. Violin Tone.

The question put before us is, what constitutes good violin tone? Some suggestions for an answer may be found in Fig. 11,

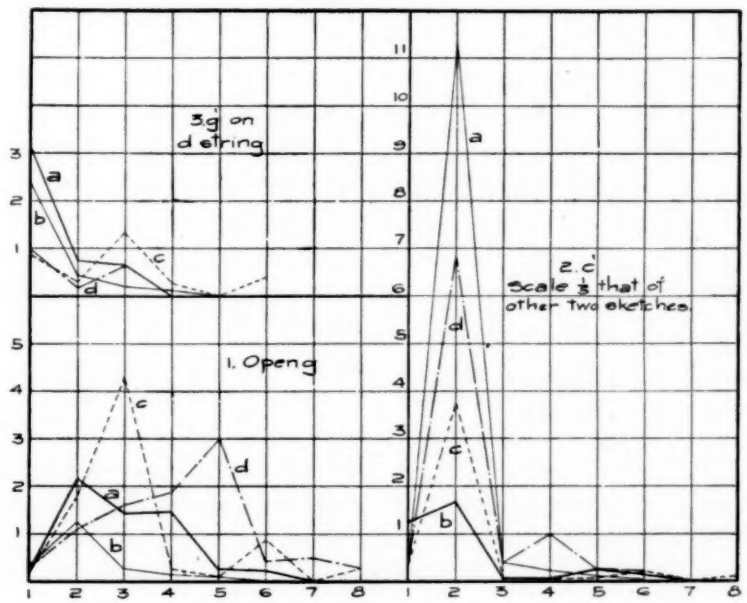


Fig. 11.

[1] It may be added that after varnishing this seemed to be an extremely good violin, as indeed will appear from the similarity of its curves to those of the best instrument shown in Fig. 11. It remains of course to see the effect of aging on its tone-quality. All the parts were adjusted and graduated with the greatest skill and care by Mr. Della Torre, who is a master in this line, and the result leads us to hope that good violins will not vanish from the world when the Cremonas wear out.

which shows the records of several instruments tested. So far as the writer can judge at present, the nearest approach to the ideal is represented in record (*a*), which is from a very valuable violin owned, and very kindly brought to the laboratory and played for me, by Professor Van Hulsteyn, of the Peabody Conservatory of Music. A rough attempt has been made to arrange the other records in order of decreasing merit of the instruments, but no great weight should be given to this order now. First a considerable number of the very best instruments should be very carefully compared in order to arrive at an idea of what ideal violin tone would be, and then it will be easier to classify various specimens by their deviations from this standard. It will be found, of course, that a great many violins will approach the standard in some parts of their range, while they will fall away from it in others.

VIII. The Vowels.

Our method ought to be useful in attacking the very interesting and unsettled question of the composition of the vowels. Figure 12 shows specimen records of a few vowels,[1] but the question is far too large to be discussed on the basis of the limited number of experiments we have so far been able to carry out in this line.

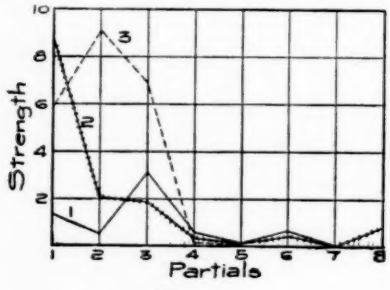


Fig. 12.

There seems no reason why some such device as this might not be used to test voices for training, first to find whether the voice has possibilities, and then to test the effects of a given method of training in bringing the voice up to what might be settled on, as indicated above for the violin, as a standard of quality for a voice of that range. Of course it is not meant that we must subject voices to an absolutely mechanical criterion, but a physical test ought to prove of great assistance.

[1]Only a very few of a number of observations are here figured, as it seems useless to give a large number of undigested results.

Summary.

1. The method devised gives *quantitative* records of the composition of sounds *actually emitted* from instruments, in terms of the energy of the partials.

2. The quality of a sound heard in a room with reflecting walls depends on the position of the instrument producing the tone, and of the hearer.

3. The lowest tones of a violin are almost lacking in fundamental.

4. Muting increases fundamental and decreases overtones in the lower tones of a violin; in the higher ones it decreases all the constituents.

5. In a good violin the lower tones are weak in fundamental and strong in the first two or three overtones, the energy rapidly disappearing towards the sixth or eighth partial. For higher tones fundamental increases and overtones die out, so that on the *a* string there is scarcely any overtone above the second partial. The seventh partial rarely appears in noticeable amount in any tone.

6. Some records were made of other instruments and of vowel qualities, but are not discussed.

My thanks are due to Professor Ames for his interest and help throughout the course of these experiments. Dr. Anderson has largely given direction to the work from the beginning, and many of the experimental details have been worked out by his assistance and that of Dr. Pfund. Dr. Watson, of the psychological laboratory, has given valuable help by putting at my disposal certain acoustical apparatus belonging to that laboratory. I cannot omit to put on record my appreciation of the helpful interest of many of the musical people of Baltimore, including several members of the staff of the Peabody Conservatory, and some musical dealers of the city.

Physical Laboratory,
Johns Hopkins University.

STUDIES IN LUMINESCENCE.

BY EDWARD L. NICHOLS AND ERNEST MERRITT.

XV. ON FLUORESCENCE AND PHOSPHORESCENCE BETWEEN + 20° AND − 190°.[1]

AMONG the earlier investigations made by the use of liquid air were the observations of Dewar[2] upon the effect of cooling various phosphorescent substances. He showed that many bodies which are phosphorescent at ordinary temperatures cease to respond to excitation at the temperature of liquid air and that numerous organic substances begin to show phosphorescence only at very low temperatures.

In 1904 the present writers[3] published an extended list of such substances with notes concerning intensity, duration, color, and the easily noted changes observed during cooling.

More recently Lenard has stated the general principle, based upon the study of numerous phosphorescent sulphides, that for each band in the spectrum of a body excited to phosphorescence there is a certain range of temperatures within which it is phosphorescent and above and below which no phosphorescence of long duration occurs, although fluorescence may be present both at higher and lower temperatures.[4]

Some Preliminary Observations of the Effects of Temperature on Phosphorescence.

A study of the rates of decay of various phosphorescent solids, including some of the sulphides investigated by Lenard, shows a more complicated set of phenomena than can be directly accounted for by his hypotheses.

[1]A portion of the apparatus used in this investigation was purchased under a grant from the Carnegie Institution.

[2]Dewar, Proc. Royal Soc., 55, p. 340.

[3]Nichols and Merritt, PHYS. REV., XVIII., p. 356.

[4]Lenard, Annalen der Physik (4), XXXI., p. 663, 1910.

For the observation of the effect of temperature upon the brightness and duration of phosphorescence down to the temperature of liquid air a layer of the substance to be studied was placed in a capsule formed by plugging one end of a brass tube about 20 cm. long and 2 cm. in diameter with a metal disk that fitted the bore of the tube snugly and was counter sunk about 4 mm., leaving between its upper face and the end of the tube a shallow cylindrical opening. This tube *t*, Fig. 102, of which only the upper end is shown, was threaded to fit within a massive cylinder of copper, *c*, which in turn fitted into the bottom of a tube of vulcanized fiber, *f*. The tube *f* was inserted in a circular opening in a box of the same material. Only a portion of the bottom and of one of the walls is shown in the diagram. The surface of the phosphorescent substance was viewed through a tube, *s*, inserted through the wall of the box and carrying a converging lens and rectangular prism at its inner end.

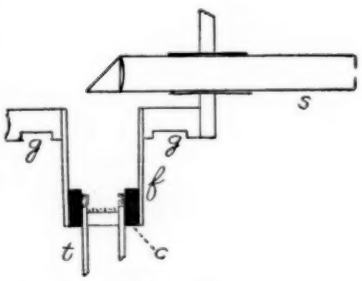


Fig. 102.

The substance was excited to phosphorescence by projecting upon its surface by means of a system of quartz lenses and a mirror of speculum metal, not shown in the figure, the light from a flaming arc rich in ultra-violet rays. In the path of the exciting light, but outside of the box, was mounted a shutter, the opening and closing of which were automatically recorded on a chronograph, thus marking the times at which excitation began and ended.

The brightness of phosphorescence from moment to moment after the close of excitation was measured by means of a simple form of photometer especially constructed for these experiments. It consisted of a broad T-tube, as shown in Fig. 103, within which a vertical sheet of glass was mounted which carried at its center a small right-angled prism. This prism received light from the ground glass screen *g* and reflected it to the eye at *l*.

The straight arm of the photometer was in line with the tube (*s*, Fig. 102) so that the observer at *l* looking past the small prism

received light also directly from the phosphorescent surface. His field of view appeared as a disk of phosphorescent light *p*, Fig. 2, in the middle of which was a square patch of light due to the prism.

The ground glass screen *g* (Fig. 103) was illuminated from without by a small tungsten lamp with frosted bulb, and by moving this lamp along a photometer bar in the prolongation of the axis of the transverse tube *c* (Fig. 103) the contrast field just described could be adjusted to equality. Suitable color screens in front of the lamp adapted its light in quality to that of the phosphorescent substance. The color match thus obtained, while not perfect, was sufficiently close to permit of satisfactory readings with the photometer.

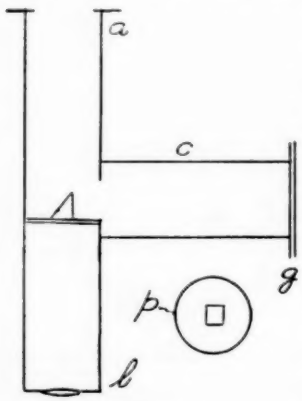


Fig. 103.

With the assistance of Mr. J. F. Putnam the phosphorescence of a number of substances was studied. To obtain the curve of decay, the comparison lamp was placed at a measured distance from the ground glass screen, the substance was excited to phosphorescence by opening the shutter for a time more than sufficient to ensure saturation, *i. e.*, ten seconds,[1] the appearance of the contrast field of the photometer was watched as the phosphorescence died away and the instant of balanced brightness was recorded on the same chronograph sheet on which the opening and closing of the shutter had been automatically registered. This operation was repeated several times, and similar sets with the lamp at various distances were made.

To obtain the corresponding curves at lower temperatures the bottom of the tube *t* (Fig. 102) was submerged in liquid air. The temperature of the phosphorescent substance was determined from the electrical resistance of a coil of fine copper wire which surrounded the top of the tube *t*, close to the substance and within the walls of the hollow copper cylinder *c*. The circular groove *gg*, Fig. 102, was cut in the bottom of the fiber box to receive the lip of the Dewar flask during the operation of cooling.

[1]It had been found by trial that with the powerful source of ultra-violet light used in these experiments saturation was attained in about six seconds.

As will be seen from Fig. 104, which contains the curves of decay of phosphorescence of a sample of zinc sulphide (Sidot blende) studied by the method just described at + 20° and − 125°, the effect of cooling this substance was to greatly hasten the rate of decay.

Both of these curves are of the well known type common to all cases of phosphorescence that have thus far been quantitatively investigated, as may be shown by plotting the square root of the reciprocal of the intensity as a function of the time, and the first and second processes of decay are distinct and well marked.

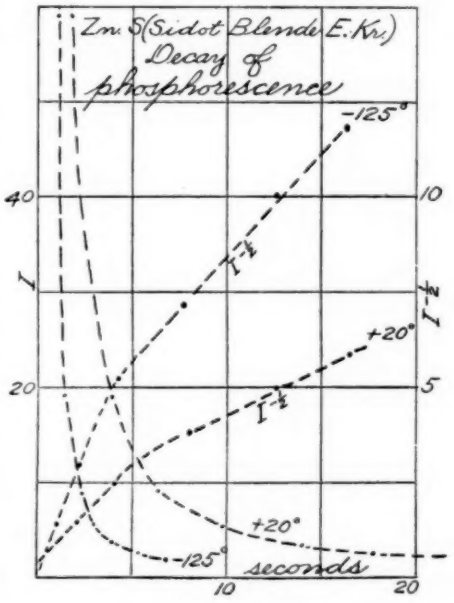


Fig. 104.

The intercepts of the curves for $I^{-\frac{1}{2}}$ show that the initial intensity at − 125° was considerably greater than at + 20° although decay of phosphorescence was more rapid.

This result appears at first sight to be in agreement with the recent dictum of Lenard that for each substance there is a temperature of maximum phosphorescence below which the activity diminishes and finally disappears. Further study however develops more complicated relations. If, for example, instead of finding the curves of decay at two or more fixed temperatures the substance is allowed to cool slowly to the temperature of liquid air and the length of time required at various temperatures, after exciting to saturation, for the phosphorescence to fall to a given brightness is recorded, the curve shown in Fig. 105 is obtained. From these measurements it is evident that there is a maximum of duration of phosphorescence at some

temperature above + 20° C., another, very pronounced, at − 40° and third below − 160°.

Similar studies of two phosphorescent sulphides of barium, prepared by the method of Lenard and Klatt, gave the curves shown in Figs. 106 and 107. The first of these sulphides, which had a trace of copper as the active metal with a lithium salt as flux, gave the characteristic yellow-red phosphorescence at + 20° with long duration; but between − 30° and − 140° its action was either too weak or too fleeting to permit of measurement with our apparatus. Upon further cooling a slight increase in the duration occurred which reached a maximum at − 160° and fell off again to scarcely measurable values at the temperature of liquid air.

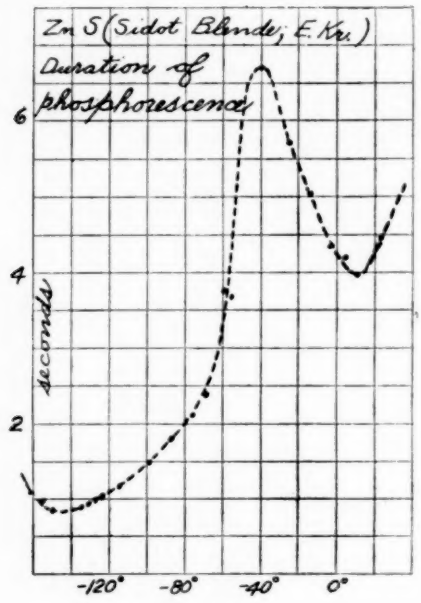


Fig. 105.

The other sulphide, the curve for which is given in Fig. 107, has bismuth as its active metal with a potassium salt as flux.

This substance shows a minimum of phosphorescent activity at − 60°, although still of measurable duration and this is followed on further cooling by a condition of greatly increased brilliancy. The crest of the curve lies at − 135° at which temperature the duration exceeds that at + 20°. Below − 135° the diminution is exceedingly rapid and before − 160° is reached no phosphorescence, measurable by this method, remains. This substance after having been observed while cooling throughout the range from + 20° to − 160° was allowed to warm very slowly and measurements were made at intervals to see whether the curve of cooling would be repeated. It will be seen that these observations, which are indicated by the symbol *x*, all lie close to the curve.

In addition to these changes in the duration of phosphorescence there are numerous cases in which the color of the emitted light changes with the temperature and others where the color shifts during decay.[1] Furthermore phosphorescence sometimes differs in this respect from the fluorescence of the same substances. Andrews[2] has described several striking instances in which a light pink

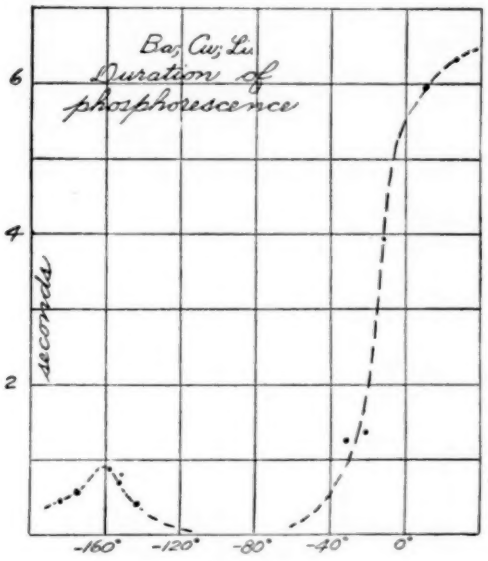


Fig. 106.

fluorescence is followed by an orange-yellow phosphorescence, yellow by light green, etc. On the other hand, the present writers have shown that a single band in the phosphorescence spectrum of Sidot blende dies away as a whole, without change in the distribution of intensities or shift of the wave-length of the maximum. These observations have been verified and extended through a much greater range of time by photographs of the phosphorescence spectrum of this substance made by Dr. C. A. Pierce.[3] If, as seems probable, this is a general characteristic of such spectra it would seem to indicate a more complex structure in many fluorescence spectra than has been commonly assumed, and in particular that many broad

[1]Nichols and Merritt, PHYS. REV., XVIII., p. 355.
[2]W. S. Andrews, Science, XIX., 1904, p. 435.
[3]Pierce, PHYSICAL REVIEW, XXX., p. 663.

bands which are usually described as single really consist of two or more overlapping components.

If the various components of such a composite band die away at very different rates, the changes of color often observed during decay would be accounted for, and if differently affected by temperature the remarkable variations in the quality of the phosphorescent light when substances are cooled by liquid air would be explained. The presence of superimposed bands, each having a

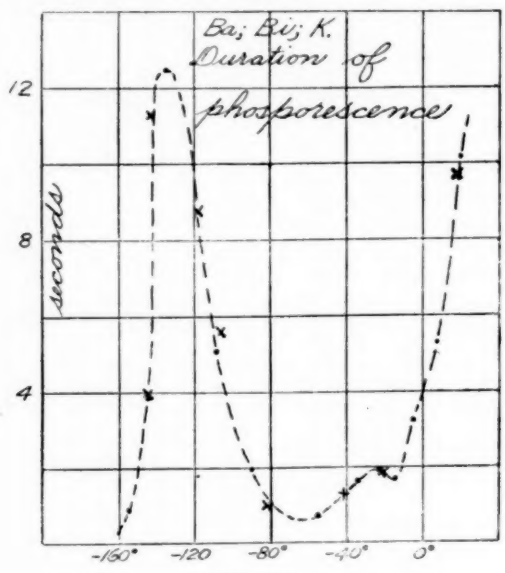


Fig. 107.

maximum of brightness at some given temperature and a maximum of duration, while the maxima for the various components of a broad band occur at widely different temperatures, would doubtless suffice to account for the phenomena already described in this paper.

For these reasons it seemed important to study the nature of these spectra more precisely than had hitherto been done and to observe in particular the effects of temperature upon their intensity, wave-length, and structure.

Some Effects of Temperature on Fluorescence Spectra.

Fluorescence lends itself more readily to precise measurements than phosphorescence because of its greater brightness and its sta-

bility, but special precautions are necessary to avoid the blending of the exciting light with that emitted by the fluorescent substance. Even a small percentage of stray light from the exciting source will greatly modify or may entirely mask the fluorescence of a body. Many fluorescent solids are not recognizable as such when illuminated by daylight on this account, and it is only when they are exposed to ultra-violet radiation or to cathode rays that their fluorescence appears. It is necessary in such cases to excite the substance by radiation of wave-lengths readily separated by dispersion from the fluorescence bands.

In the measurements to be described the apparatus was similar to

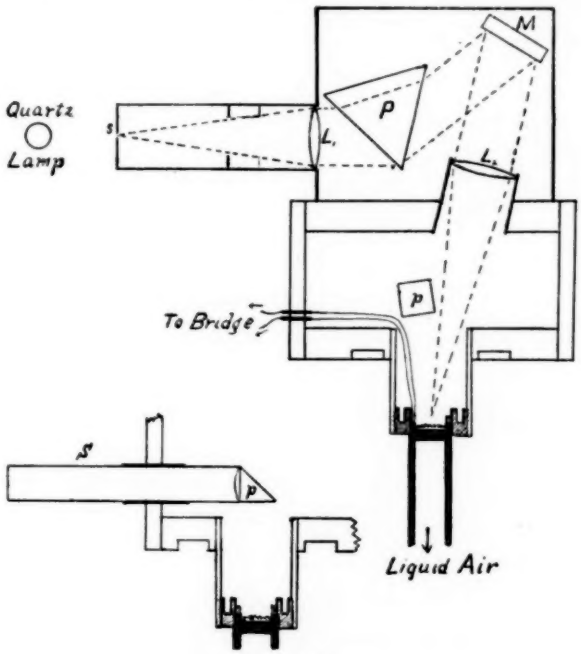


Fig. 108.

that shown in Fig. 102, but the source for excitation was a mercury arc in quartz, the light from which was dispersed by the quartz system $L_1P_1L_2$ (Fig. 108). By turning the mirror M any desired portion of the mercury spectrum could be thrown upon the surface of the substance under observation. The arrangements for cooling by liquid air and for measuring the temperature were those already described.

Instead of the photometer, however, one collimator of a Lummer-Brodhun spectrophotometer was placed in line with the sighting tube, S, and received the fluorescence light from the specimen. As a comparison source an acetylene flame was used and the illumination of the comparison slit was varied by moving this flame, properly housed and screened, along a photometer bar. In this way the troublesome corrections for slit-width discussed in a previous communication[1] were avoided.

By this method the brighter bands of several fluorescent liquids and solids were carefully measured, wave-length by wave-length.

In each case as narrow a slit was used as the brightness of the band would permit and care was taken to locate the crest by means of readings made alternately on either side at wave-lengths successively nearer together. The most convenient and successful method consisted in locating the comparison flame at some point on the bar such that the intensity of its spectrum in the region of the crest would be considerably less than that of the brightest portion of the band, and exploring the fluorescence spectrum for regions in which it and the comparison spectrum were of equal intensity. A repetition of this process for various intensities of the comparison flame affords data from which a complete map of the band or group of bands may be plotted.

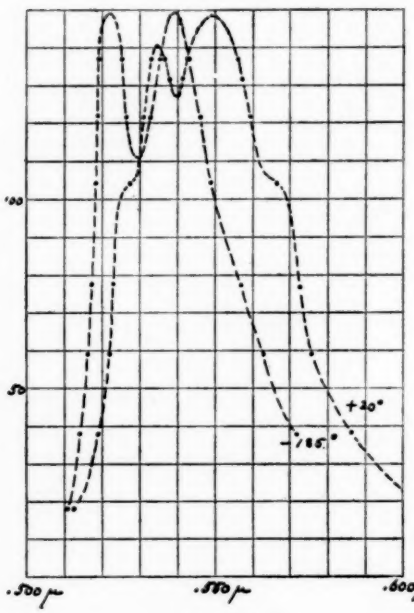


Fig. 109.

Fig. 109 shows the results of measurements of an alcoholic solution of fluorescein which we studied in the manner described when excited at + 20° and − 185°. What appears by ordinary spectro-

[1]Nichols and Merritt, PHYS. REV., Vol. XXXI., p. 500.

scopic inspection to be a single broad band extending from about .500μ to beyond .600μ is found at + 20° to consist of at least four overlapping bands with crests at .528μ, .534μ, .550μ and .567μ. Two of these bands appear merely as shoulders upon the sides of the curve. Upon cooling to − 185° there is a marked shift towards the violet, a narrowing of the composite bands and complete disappearance of the two shoulders. The crest towards the violet is increased in brightness and the yoke between the crests is much deeper. At this temperature one might under favorable conditions recognize the doubleness of the band by inspection with an ordinary spectroscope.

That these changes are not entirely due to the freezing of the solution may be seen from Fig. 110, in which the form of the band is given at + 20° and at − 80°. The shift at the latter temperature

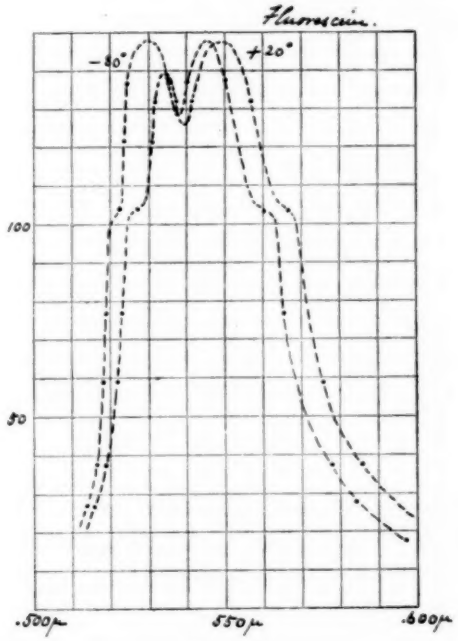


Fig. 110.

is only .004μ as compared with .012μ at the temperature of liquid air and there is no deepening of the yoke. The shoulders on either side are still present, and while there is a slight narrowing owing

to a greater shift of the red side than of the violet side of the band below the shoulders there is a widening of the upper part of the curve on account of the growth of the crest at .530μ, which at $-$ 80° is broader than that towards the red.

The most interesting interval in the study of this substance, however, lies between $-120°$ and $-160°$. At $-120°$ (see Fig. 111) the fluorescence band has been greatly narrowed by loss on the side towards the red. Both peaks are narrower than at higher tem-

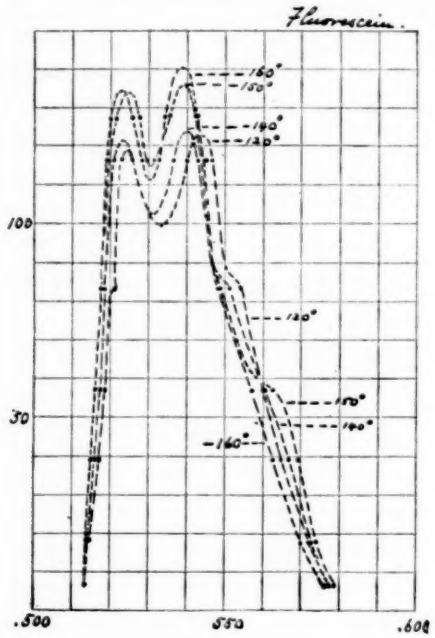


Fig. 111.

peratures, particularly the one towards the violet, which has shifted further towards the violet. The height of the crests is lower than at any other temperature at which measurements were made. The shoulders are still present, although that towards the violet, .620μ, has nearly disappeared. Between $-$ 120° and $-$ 140°, the shoulder at .555μ gradually disappears while at $-$ 140° a new shoulder between .560μ and .565μ begins to develop. This has become very prominent at $-$ 150° but is gone again at $-$ 160°.

These, or any similar set of movements and changes in fluorescence

bands can undoubtedly be accounted for, by assuming a sufficient number of superimposed components each having its fixed position in the spectrum and each changing in intensity independently with the temperature. These elementary bands, on the other hand, may be supposed to shift with temperature and to change in width as well as in brightness.

That in the obviously complex band of fluorescein under discussion there are regions very differently affected by temperature is shown in Fig. 112 in which the variation of certain wave-lengths

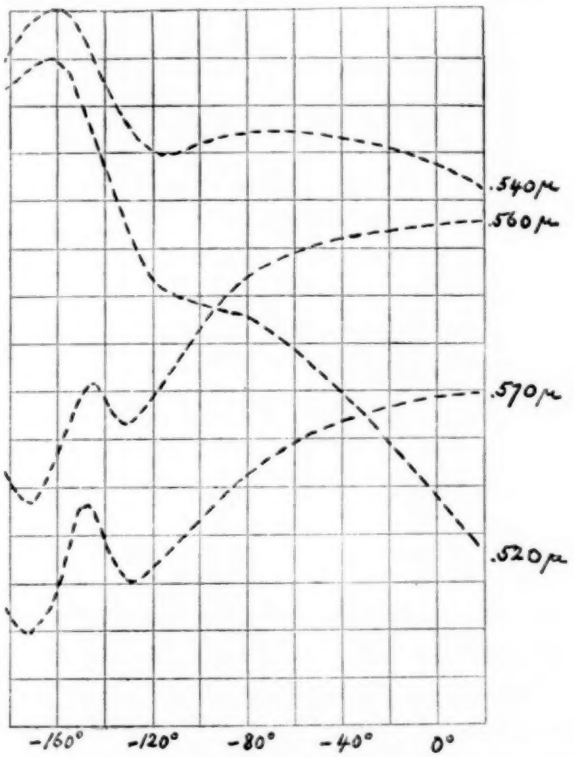


Fig. 112.

is traced throughout the range of temperature from + 20° to − 180°.

If wave-lengths on the violet side of the band are selected curves are obtained of which those for .520μ and .540μ in the figure are typical, whereas on the side towards the red, from .560μ to .570μ,

quite a different type occurs showing on the whole decrease of intensity on cooling.

Several other examples of independent variations with temperature of different parts of a fluorescence band have been observed in the course of our work. An interesting case is that of Sidot blende (Fig. 113) in which the regions about .514μ and .452μ were compared.

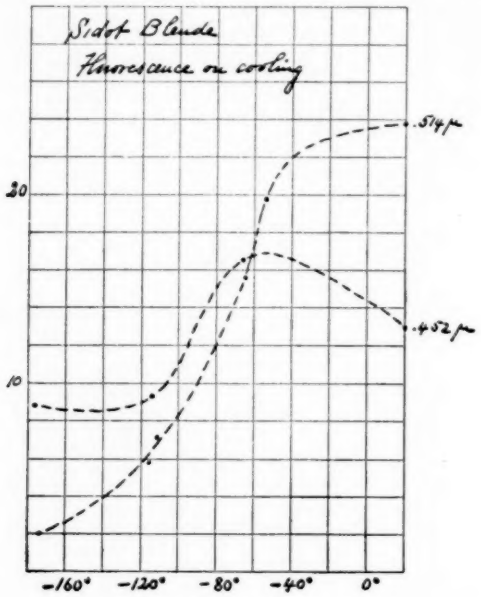


Fig. 113.

At + 20° the ratio of intensities .514μ/.452μ, the corresponding regions in the spectrum of the acetylene flame being as usual the basis of comparison, is 1.83. At − 63° it is unity and at − 175° it is 0.23. This denotes a marked change in the color of the fluorescence of this substance when cooled to the temperature of liquid air.

Two crests of the rather complicated fluorescence band of the phosphorescent sulphide designated as Ba, Bi, K in an earlier paragraph of this paper were studied in the same way and the results are shown in Fig. 114.

Not all fluorescence bands are so complex as that of fluorescein. A sample of natural willemite, mapped at various temperatures, gave the set of curves in Fig. 115. The only sign of complexity is

the slight shoulder on the side towards the violet in the curve for + 20°. At − 90° this has vanished and that side has moved towards the longer wave-lengths, but there is no appreciable shift of the crest and the side towards the red is coincident with that of the curve for + 20°. At − 165° there is a decided shift of the entire curve towards the red, narrowing of the band, and a considerable reduction of intensity.

The very interesting behavior of the fluorescence band of a dilute solution of resorufin in alcohol is illustrated in Figs. 116 and 117.

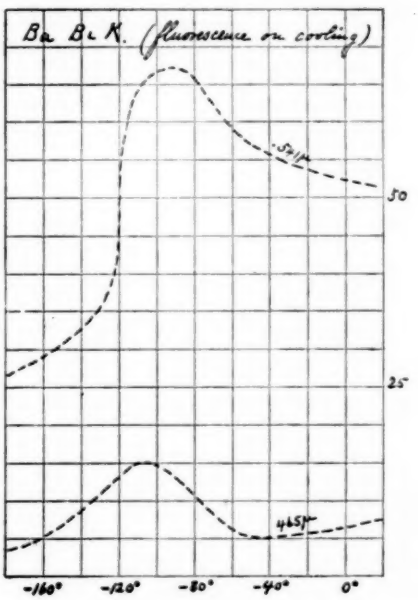


Fig. 114.

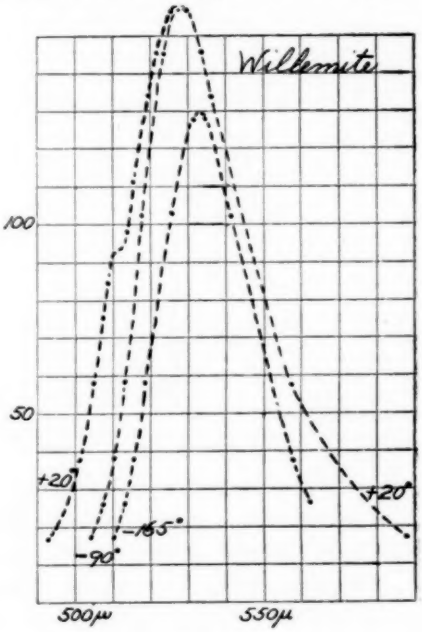


Fig. 115.

This band is typical of what we have regarded in all our previous work as a single simple band. It retains its form accurately at all four of the temperatures at which it was measured. Upon cooling to − 90° there was diminution of intensity at the crest to about one-half, but no appreciable shift. On further cooling to − 165°, during which process the liquid was solidified, there was shift from .593μ to .596μ and when the temperature was reduced to − 185° there was great increase in temperature without further shift. From this case alone one might be inclined to connect the shift with

the change of state but for the fact that a very similar movement occurs in solids, such as willemite, just described, anthracene, etc.

Resorufin is an exceptional case in its simplicity. In most instances the study of fluorescence and phosphorescence by the methods described in this paper is rendered almost futile on account of the complexity of the phenomena and the fact that one is compelled to be content to observe the resultant of movements which

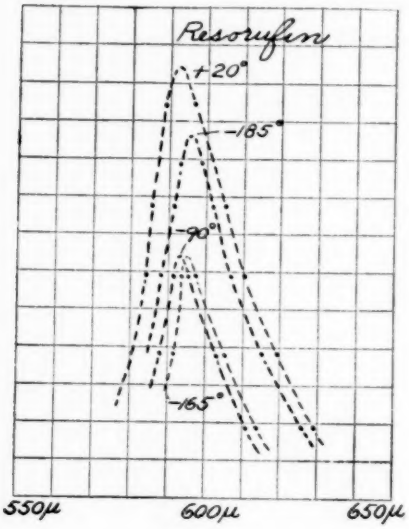


Fig. 116.

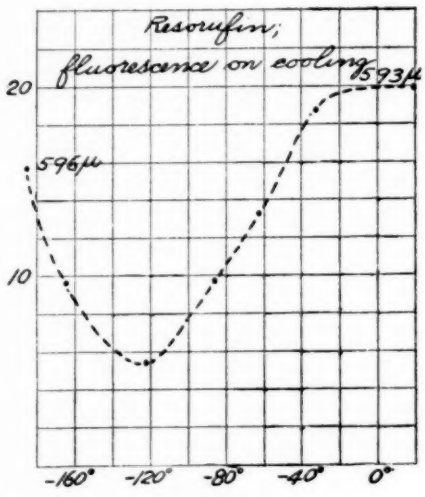


Fig. 117.

we can hardly hope to analyze and the components of which we have not as yet succeeded in separating.

One very interesting class of substances in particular, the phosphorescent sulphides of Lenard and Klatt, yield as the result of investigation with the spectrophotometer only evidence of the extreme complexity of their bands and of the complicated changes when the temperature is modified.

One example out of many will serve to illustrate the character of the phenomena. In Fig. 118 are the curves for one of these substances, a strontium sulphide with barium as the active metal and a sodium salt as flux. The curves of its band are given from measurements at + 20° and − 190°.

Since we cannot isolate the numerous components of such a group

we must seek simpler cases for our preliminary studies, and these are to be found in the double band .534μ and .502μ of commerical anthracene, the parts of which can be measured separately, and the

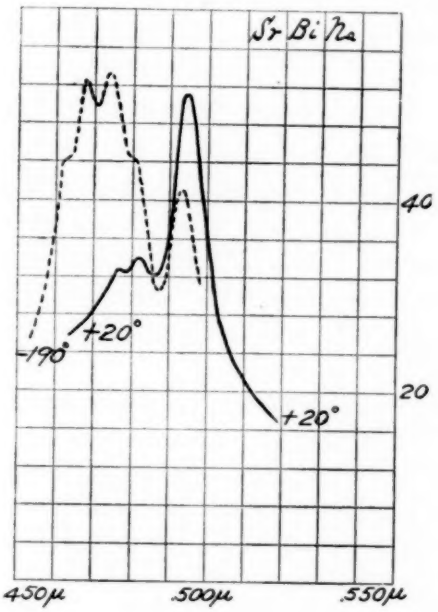


Fig. 118.

narrow single line like bands of the uranyl salts recently studied by photographic methods at various temperatures by Becquerel.[1] Of these we are now making a detailed spectrophotometric study, the results of which we reserve for a separate communication.

PHYSICAL LABORATORY OF CORNELL UNIVERSITY,
May, 1910.

[1]Becquerel, Onnes, and Pauli, communications of the Physical Laboratory of the University of Leiden, 111, 1909.

PREPARATION AND PROPERTIES OF THE HEUSLER ALLOYS.

BY A. A. KNOWLTON.

SINCE the discovery by Heusler in 1903 that it is possible to prepare strongly ferro-magnetic alloys of the non-magnetic metals copper, manganese and aluminum important papers concerning the properties of these alloys have been published by Heusler,[1] Starck, Take, Gumlich, Guthe and Austin, McLenan, and others. The most important facts as developed by these investigators may be briefly summarized as follows.

1. The magnetic permeability of the best specimens is about that of cast iron. Hill reports one specimen having an induction of 11,000 in a field of 8 c.g.s. units. This value is however considerably above that obtained by other observers.

2. The permeability is often greatly increased by annealing for some time at a temperature a little above 100° C. At higher temperatures the alloys become non-magnetic and this transformation may be irreversible so that upon cooling to room temperature the specimen is sometimes found to have suffered a partial or, in some cases, even a total loss of magnetic quality.

3. The most strongly magnetic alloys were found by Heusler and Starck to be those containing manganese and aluminum in atomic proportions; *i. e.*, in the ratio of two parts by weight of manganese to one of aluminum. Largely upon this ground it has been quite generally assumed that the copper plays no part in the alloy except as a solvent for a magnetic manganese-aluminum alloy which would otherwise be too hard and brittle for experimental use.

4. Other trivalent metals as arsenic, antimony, or tin may be substituted for the aluminum but the alloys thus obtained are much inferior to those containing aluminum.

5. Zahm and Schmidt have found a Hall effect in these alloys of

[1]For bibliography of references to the papers cited see an article by Stephenson, PHYS. REV., vol. 31, p. 252, 1910.

the same sign as in iron but larger than in any substance previously studied.

6. Ingersoll has found that these alloys do not show the Kerr effect. This is of special importance both on account of the theoretical importance of the phenomenon itself and because it is the only way in which the magnetic properties of these alloys are strikingly different from those of iron.

As nearly all observers had found occasion to complain of the poor mechanical quality of their specimens it seemed best at the outset to undertake such a study of their preparation as should, if possible, overcome this difficulty. An account of the methods finally adopted and results obtained constitutes the first part of this paper. Later fourteen specimens prepared in the winter of 1908 were tested with respect to their electrical conductivity, magnetic properties, crystalline structure, and changes under heat treatment.

The first stage of the preparation consisted in dissolving manganese in molten copper. On account of the great affinity of manganese for silicon a graphite crucible must be used and it is even then impossible to employ any flux without causing the metal to eat rapidly into the crucible. To secure a uniform mixture the melt must be kept hot for several hours and stirred frequently;—or the same result may be obtained with less loss by oxidation if the bath is cast and remelted several times. The materials used were ordinary electrolytic copper and, at first, chemically pure manganese. Later commercial manganese obtained from the Goldschmidt Thermit Company was used with apparently equally good results. To the copper-manganese melt aluminum in slightly more than the calculated amount was added and the bath cast and remelted several times to ensure a uniform mixture. Stirring should be avoided during this part of the operation because of rapid oxidation of the aluminum. Even under the best conditions of working with small quantities of material the loss in this way is considerable and uncertain so that the proportions by analysis may vary widely from those of mixing. After several remeltings the alloy was cast in graphite molds made by boring a one eighth inch hole in an arc furnace electrode. To provide for a uniform rate of cooling in all parts of the casting these molds were heated before use to a tempera-

ture slightly above the melting point of the alloys which was about 850° C. The very heavy slag which forms instantly over any exposed surface makes it essential that the metal be poured rapidly in an unbroken stream. The molds containing the still molten alloy were covered over with a layer of asbestos wool of such thickness as to allow the temperature to fall to 250° C. in about an hour. When this temperature was reached, as indicated by a thermocouple in contact with the molds, the casting was quenched by immersion in cold water. Specimens prepared in this way were of excellent mechanical quality, free from flaws and blow holes and, in many cases malleable to a considerable degree. As will appear later the magnetic test appears to indicate that a somewhat slower rate of cooling and a slightly higher temperature of quenching might have been advantageous. From a considerable number of specimens thus prepared fourteen were selected at random for examination. These were wet ground with emery to a uniform diameter of six millimeters and tested as hereafter described.

The following table (I.) gives the chemical composition and density of each specimen.

TABLE I.

Specimen.	Cu.	Mn.	Al.	Si.	Density.
1	66.6	25.9	6.8	.73	6.72
2	67.2	22.5	10.0	.25	6.77
3	64.9	22.0	12.6	.49	6.83
4	66.9	22.3	10.4	.35	6.85
5	65.0	25.8	8.8	.40	6.86
6	62.4	26.2	12.2	.24	6.88
7	62.0	29.6	8.2	.24	6.89
8	56.4	29.6	13.1	.89	6.94
9	69.6	22.1	9.1	.20	7.08
10	65.8	26.0	7.7	.49	7.12
11	70.4	19.0	9.4	1.22	7.13
12	69.2	22.1	8.4	.32	7.14
13	72.6	20.1	7.05	.23	7.16
14	72.2	17.4	10.3	.08	7.17

In general the density was found to increase slightly on annealing at 120° C. This increase never exceeded one third of one per cent. although it appeared to take place in all cases. Hill has reported variations in density of much greater magnitude under similar

treatment. From his description it seems likely that this was a result of working with a poor mixture due to insufficiently prolonged heating. The variation in the per cent. of silica is probably caused by variations in the condition of the crucible used; a new crucible giving up more silica than one which has been in use for some time. The hardness of the various samples bears a very evident relation to the amount of silica present, No. 11 for example being very hard and brittle while No. 9 and No. 14 are soft and malleable. The use of silica-free crucibles would doubtless be advantageous. A trace of iron was present in all cases. The observed density is greater than that calculated from the composition for specimens having less than 22 per cent. of Mn while for those of higher Mn content the observed density is usually less than the calculated. The greatest difference shown by any specimen is in the case of No. 11 with an observed density 5 per cent. greater than that calculated. A considerable shrinkage frequently occurs in the specimens of good magnetic quality, although it was not possible to show any relation between the two phenomena.

Electrical Resistance and Temperature Coefficient of Resistance.

McTaggart and Robertson[1] measured the electrical resistance of eight specimens of varying composition and obtained results ranging from 19.31×10^{-6} to 68.36×10^{-6}. These observers also found that the resistance-temperature curves for several of their specimens showed strongly marked minima which were not at the same temperature for the different samples. Both on account of the very wide difference in resistance found for specimens not very different in composition and because the presence of minima seems at variance with theory it appeared of interest to determine the resistance and temperature coefficient in the case of alloys prepared under different conditions. For the measuring of resistance a Thomson double bridge was used. As it was necessary to carry on magnetic measurements at the same time the apparatus was arranged as shown in Fig. 1.

A solenoid S 33.1 cm. in length and 4.5 cm. internal diameter

[1]Bul. Roy. Soc., Canada, 5, 1908, p. 31.

was wound with 1,380 turns giving a field of 49.4 lines per ampere. A cylindrical tube of soapstone 3.3 cm. external diameter was double threaded and wound non-inductively with high resistance wire. This heating coil was covered with asbestos and placed in the axis of the solenoid S which was protected from excessive heating by forcing a blast of air through the space between the heating coil and the solenoid. The specimen to be tested was supported in the axis of this system by means of the clamps used for connection to the double bridge. Temperatures were measured with a mercury thermometer since convenience was of more importance than great accuracy in this part of the work. The correctness of thermometer readings was checked before and after the observations. In the

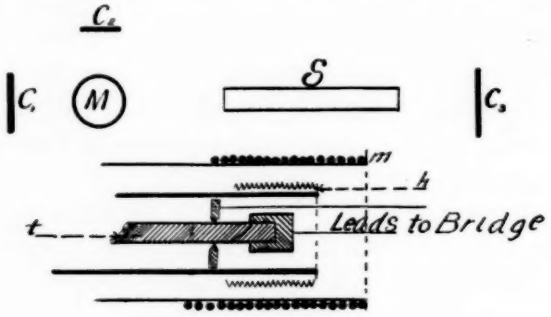


Fig. 1.

magnetic tests the magnetometer deflection method was used, the effect of the solenoid S being compensated for by the method described by Ross and Gray,[1] and proper corrections made for the end effects of the specimen itself. Table II. shows the values ob-

Table II.

No.	σx 10⁵	$a x$ 10⁴	I	No.	σx 10⁵	$a x$ 10⁴	I
1	47.9	23.5	81	8	62.7	15.7	112
2	53.0	23.0	251	9	60.6	15.5	246
3	59.3	13.9	284	10	64.2	13.5	208
4	45.9	27.3	331	11	56.0	13.4	152
5	45.4	22.7	331	12	60.8	11.8	160
6	46.4	24.6	332	13	54.9	15.3	172
7	48.9	18.4	212	14	55.9	9.1	4.8

[1]Proc. Roy. Soc. Ed., 29, 1908, p. 182.

tained by electrical and magnetic measurements upon the specimens in their original condition. The external field H' was constant and equal to 80 lines/cm.^{2} during these tests. No correction is here made for end effects.

The variation in the value of the specific resistance (σ) for different specimens, while much less than that found by McTaggart and Robertson, is still larger than can be accounted for by differences in composition. Later work indicates that a slower rate of cooling would have given more uniform results. The variation of σ with temperature is shown in Fig. 2 which is a set of curves for specimen 3 but wholly typical of what happens in every case. The curves are straight lines differing from those for a pure metal only in slope and in that at certain temperatures the resistance undergoes a permanent decrease with time; a process of artificial aging frequently met in alloys. The numbers given in the diagram indicate the time which elapsed between the lettered readings; *e. g.*, in curve II. the reading at C was taken two hours after that at B. The microscopic examination which was carried on in connection with this part of the work showed that each decrease in resistivity accompanied an improvement in crystalline structure and that any treatment, such as quenching from a comparatively high temperature which impaired the crystallization was accompanied by a corresponding increase in resistivity, an increase which in one case amounted to doubling the value before quenching. There was no indication that the resistance depended at all upon the kind of crystals. The temperature coefficient (α) which was originally very low and lowest for the specimens of highest resistivity increased as the resistance at zero decreased and in nearly the same ratio as is shown by the fact that the successive curves are parallel. The fact that the descending branch of curve II. does not fall exactly upon the ascending branch of curves III., IV. and V. is probably due to an error in measuring the length between the clamps of the double bridge. It will be noticed that after five hours at 140° the succeeding heatings represented by III. and IV. (both of which began at 28°) produced no effect, but that above 160° a second rapid decrease in resistivity took place until a second condition of stability was reached which persisted until the temperature was raised above

225°. In some later work it has been found that these three temperatures are important transition points for many specimens. The only way in which these alloys are different from many others in respect to their conductivity is in the degree of their sensibility to

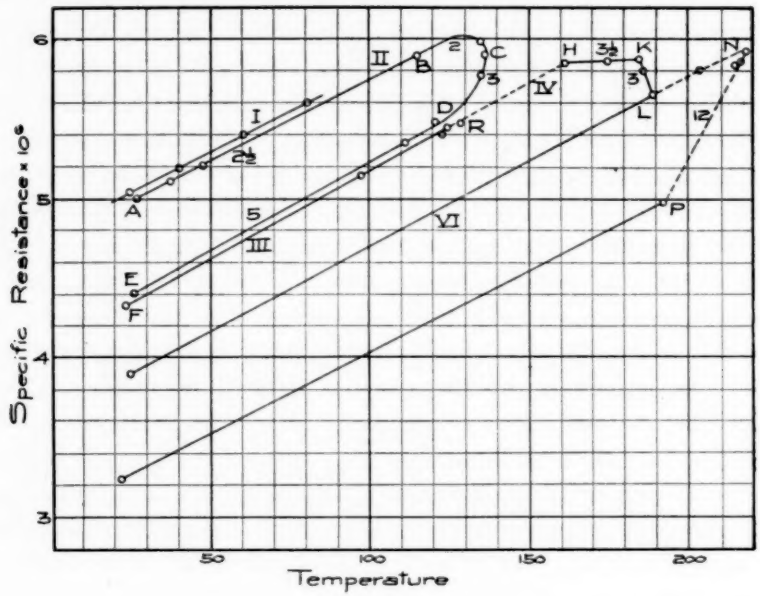


Fig. 2.

annealing processes and this is altogether due to the ease with which their crystalline structure undergoes modification, as is shown in a later part of this paper.

Relation of Magnetic Quality to Crystalline Structure.

During this part of the work several of the specimens were subjected to extensive cycles of heating in the furnace previously described, magnetic measurements being made before and after each cycle and at such other temperatures as seemed desirable. Before and after each cycle one end of the specimen was polished and etched with a mixture of hydrochloric acid and ferric chloride. This mixture was adopted after experiments with many etching agents because it was found to give more uniform results than any other, and also because the coloring action of the ferric chloride

greatly increased the contrast between the different crystals. In this way very complete studies were made of specimens 2, 3, 7 and 10, and work enough done on all others to determine their transformation points and to show that their general behavior was similar to that of the specimens more extensively studied. An outline of the treatment to which a single specimen (No. 7) was subjected, together with some account of the results obtained, is given in tabular form in Table III. The total time of annealing in this case was somewhat more than a hundred hours, and the value of the magnetization reached varied from about 400 c.g.s. units to zero with corresponding variations in crystalline structure, as is shown in the accompanying microphotographs.

TABLE III.

Temp. Max.	Hrs.	I	$\sigma.r\ 10^6$	Photo.	Remarks
—	——	298	50	30	16 months after casting.
100	10	351	42.1	31	
133	3.75	376	41.7	32	Curve I.
160	4	385	38.9	—	
225	5	270	35.4	35	
290	2	350	35.4	36	Curve II.
100	5	——	——	—	Heating continued without cooling.
206	2	350	——	—	No marked change.
225	1	253	——	—	Curve IX.
225	3.5	153	35.6	36	Curve XIV.
300	5	206	——	38	
250	9.5	118	——		Curve XIX.
350	.25	145	——	39	Cooled rapidly.
290	5.75	123	——	40	Cooled slowly.
350	2.5	219	——	41	Curve XXIV.
275	5.5	80	39.1	42	
350	5	—	60.6	43	Quenched. Non-magnetic.
250	3.5	—	——	—	No effect.
400	4	—	——	—	No effect.

A comparison of the value of I in Table III. with that for the same specimen (No. 7) in Table II. shows an increase from 212 to 298 in the intensity of magnetization for the same field strength. This increase, which amounts to 40 per cent. of the original value, took place at ordinary temperatures during a period of sixteen months. Heating to temperatures up to 160° apparently completed

in something less than 20 hours the transformation which had been going on slowly at room temperatures. Although the maximum intensity of magnetization was slightly increased by the last heating (160°) the specimen was at the same time rendered much harder magnetically by this treatment. Heating at 225° for five hours caused a 25 per cent. decrease in the value of I while two hours at 290° restored the specimen nearly to its best condition (curve II.). Subsequent heatings at temperatures below 225° produced no effect, curve V. which was taken after two hours at 100° and an equal time at 206° being identical with curve II. Even a short time at 225°, however, produced a marked change as is shown by curve IX. and the loss of magnetic quality continued on further heating at 225° and 250° (curve XIV.). Partial recovery again followed heating to 300°. Nine and one half hours between 225° and 250° left the specimen very poor magnetically (curve XIX.) with the expected recovery at 300° or slightly above (curve XXIV.). After this heating to 350° it was noticed that the alloy reacted to the etching agent (HCl and $FeCl_3$) very differently from its previous behavior. Up to this point there had been no tendency to deposit copper even when the etching was continued for from five to eight minutes, but on attempting to etch following this heating a coating of copper so thick as to entirely conceal the structure was deposited in less than a half minute. This of course indicates a breaking up of some of the crystals. Chilling from this temperature left the alloy non-magnetic and it was not found possible to render it magnetic again by any thermal treatment although after some months at ordinary temperatures it was found to have become appreciably magnetic again.

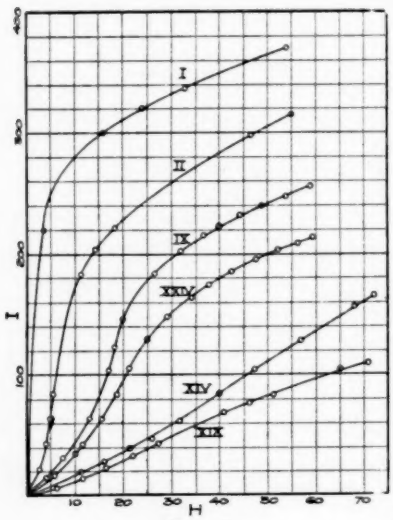


Fig. 3.

These results are in good accord with those of Asteroth who

states that he found it possible to control hysteresis losses by the rate at which his specimens were cooled through the transformation temperature. The writer's interpretation of the phenomena is, however, somewhat different. Transformation from the magnetic to the non-magnetic state takes place over a range of about 50°, the lower limit for this particular specimen being 225° where the loss of magnetic quality begins to take place rapidly and the upper limit being 275° where the specimen is totally non-magnetic. Annealing at the lower limit leaves the alloy very hard and with a low maximum induction while annealing at the upper limit followed by moderately rapid cooling softens the specimen and increases the maximum induction. This was found to be the case with all specimens examined.

So far as the permanent changes which take place on heating are concerned they may be explained if we assume that the magnetic properties belong to molecular groups which are constituents of a certain type of crystals which form at temperatures in the neighborhood of 300° and are stable at ordinary temperatures but pass through a meta-stable condition between 225° and 275°, while the non-magnetic crystals which constitute the stable form within this range are meta-stable both at 300° and at room temperatures. An examination of the micro-photographs taken in connection with the curves of Fig. 3 as indicated in the table appears to verify this assumption since a certain type of crystal is found to increase on annealing at either 100° or 300° but disappears, to a considerable extent, on annealing at 225°.

The micro-photographic examination which was carried on in connection with the magnetic testing showed that the alloys contain crystalline masses of three distinct sorts as seen in the photographs of Fig. 4. The etching agent was in all cases the hydrochloric acid-ferric chloride mixture previously referred to and a magnification of about 200 diameters was used in all cases.

Photograph no. 24 is a copper-manganese alloy (Cu 70 per cent.) such as was used as a basis for the preparation of the Heusler alloys. It is included to show the striking change in structure produced by the addition of aluminum. Photographs 36–37–38–41–44 are of No. 7 and show the structure corresponding to the curves previously de-

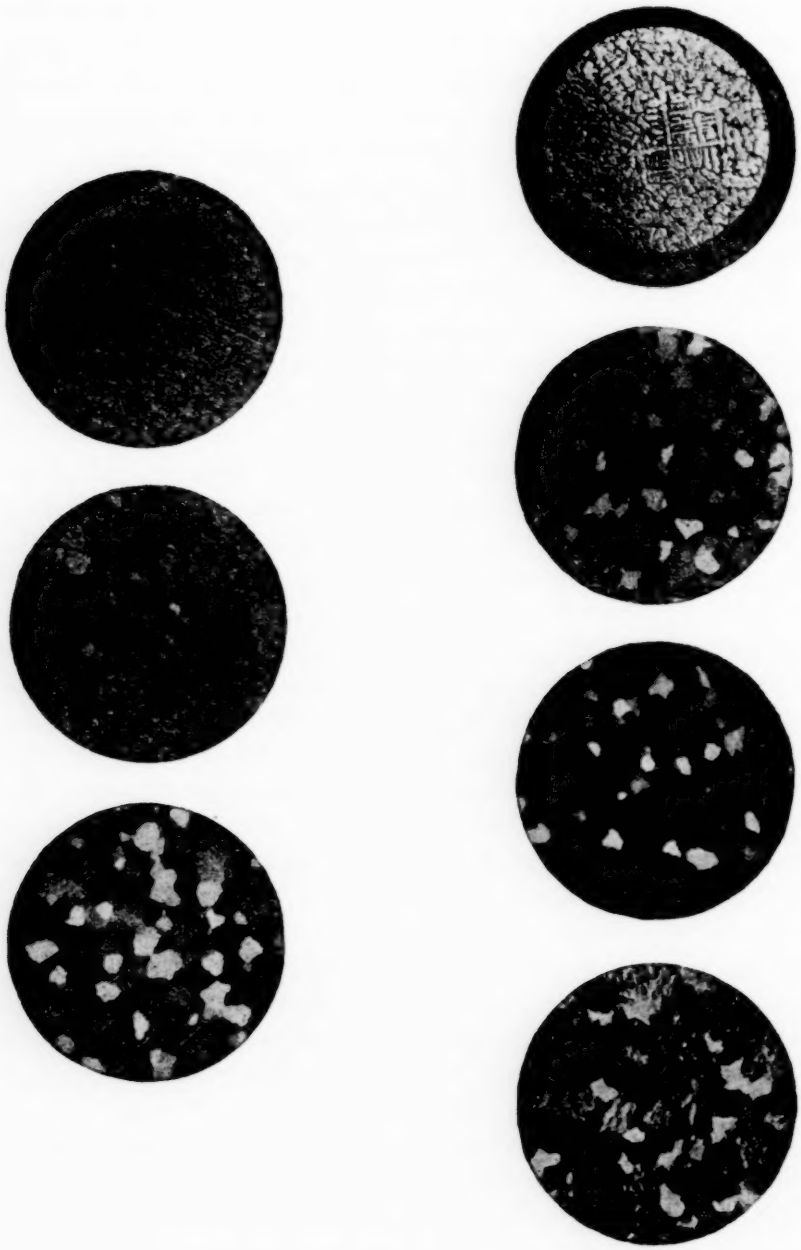


Fig. 4.

scribed as indicated in Table III. Of the three sorts of crystalline masses (white, dark gray and black) those which are unaffected by the reagent and consequently appear white in the prints are by far the most striking and show the widest range of variation. It will be noticed that the area of the photograph covered by these crystals is large in all cases where the specimen was highly magnetic and decreases with loss of magnetic quality (compare 36 and 38, strongly magnetic; with 37, weakly magnetic; and with 44, non-magnetic). No. 41 was taken after the first heating to 350° and amply confirms the supposition as to the breaking up of the crystals already discussed. On account of the rapid deposition of copper in this case it was necessary to etch in relief by polishing with rouge on a soft cloth moistened with the etching agent. The spidery matrix, not present in any previous photograph, is left in relief while the crystalline masses are etched out to a considerable depth and hence are less perfectly differentiated than in cases where a more even illumination was obtained. To the eye the matrix appears yellow and evidently consists of nearly pure copper. Of the crystals some are much pitted and roughened while others retain a polished surface. In 44 every trace of the characteristic structure has disappeared along with the magnetic properties. The specific resistance in this condition was 70 per cent. greater than in the condition represented by 38.

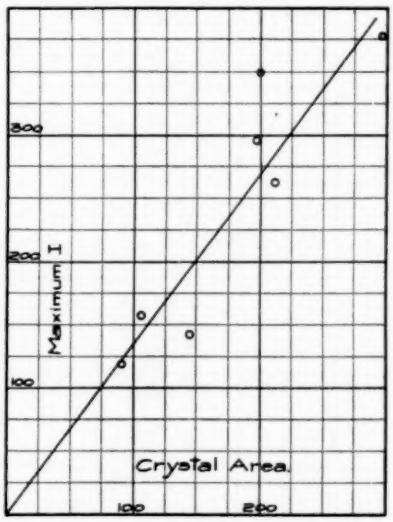


Fig. 5.

So marked was the relation between structure and magnetic quality that after some experience it was found possible to make a fairly accurate estimate of the value of I at saturation from a visual examination of the structure. The areas covered by the white crystals on a number of photographs both of this and other specimens were estimated by means of squared paper, and within

the limits of error which are naturally large, these areas appear to be proportional to the values of I at saturation. Fig. 5 shows this relation for a number of cases.

A striking confirmation of the hypothesis that the white crystals contain the magnetic units was afforded by specimen No. 14 which was originally supposed to be non-magnetic and was included in the lot under test to see if it could be rendered magnetic by heat treatment. When photographed the specimen showed the white crystals which had in all other cases been found associated with good magnetic quality (photo. 54). At the time the contradictory results were unexplainable. On determining the transformation temperatures the specimens were found to divide into two groups. In one

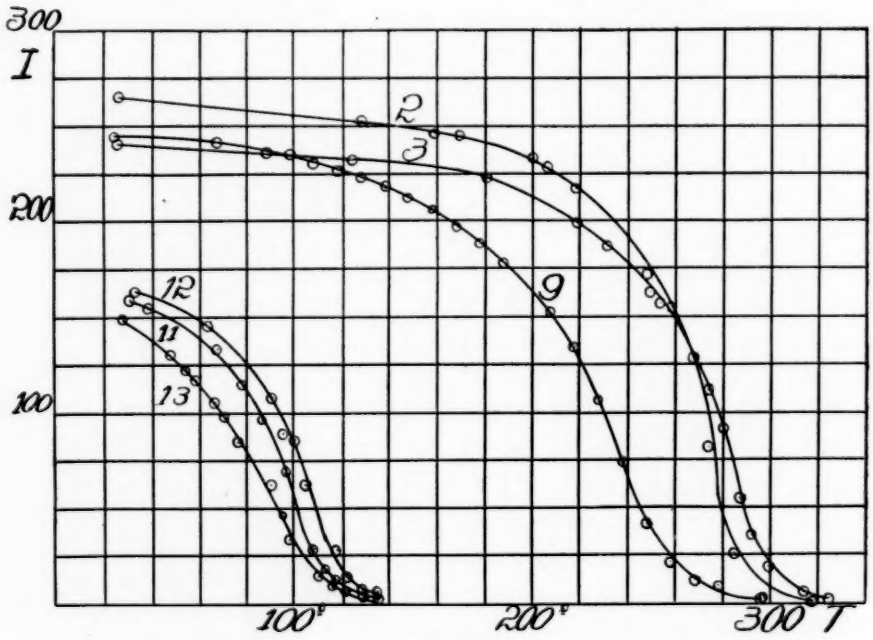


Fig. 6.

group transformation to the non-magnetic state was complete at 275°, in the other at 135° as shown in Fig. 6.

This suggested that No. 14 might have a still lower transformation point and trial showed this to be the case, a small telephone magnet lifting it readily from a cake of ice only to have it drop off after a minute or two as the temperature rose. Fig. 7 is an I–H curve for

this specimen at zero, the heating coil of Fig. 1 being replaced by an ice bath. The extreme softness is characteristic of all specimens near the upper limit of transformation. The value of I at saturation would have been considerably greater at a still lower temperature as shown by the transformation curve which was still rising rapidly at zero.

Although the differences in chemical composition did not appear sufficient to account for the observed differences in the transforma-

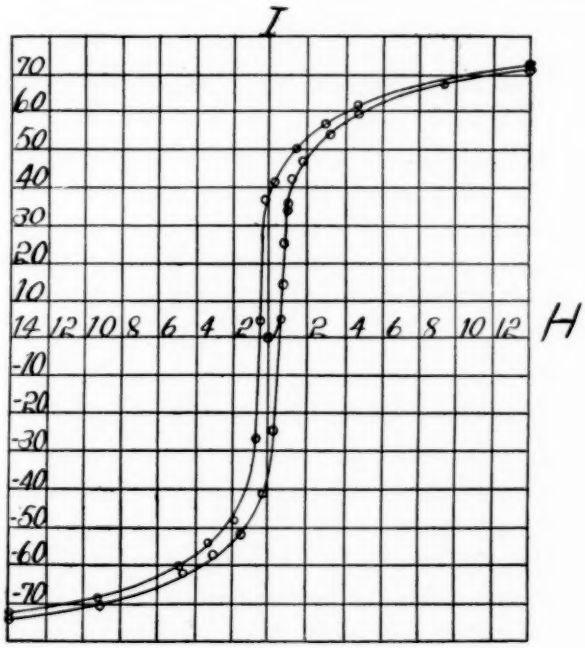


Fig. 7.

tion temperature, no other cause could be assigned since in no case did the heat treatment appear to produce any change in this regard. An attempt to reproduce the alloys of low transformation temperature by making specimens having a high ratio of copper to manganese (Cu 72, Mn 18, Al 10) was successful. This result is in line with the work of Ross and Gray in indicating that the copper plays a part of much greater importance than a mere solvent for a Mn-Al alloy as has frequently been assumed to be the case.

Since the white crystals are always present in magnetic specimens and are never found in specimens which are not, under proper

conditions, magnetic and since there seems to be a simple relation between the quantity of crystals of this kind and the magnetic quality it seems fair to assume that they contain the magnetic constituents of the alloy. Attempts to isolate these crystals were unsuccessful. The fact that these crystals may, as is seen in the photograph of No. 14, exist when the specimen is above its transformation point would seem to indicate that the magnetic quality depends in some way upon the internal structure of the crystal and that this molecular grouping is, in turn, for an alloy of given composition, dependent upon the temperature. A surprising feature is the apparently slight difference between the magnetic and non-magnetic states as indicated by the fact that careful experiments with an apparatus of great sensitiveness failed to show positive evidence of any evolution of heat on passing through the transformation range.

Since the above was written Stephenson (PHYS. REV., vol. 31, p. 252, 1910) has published curves indicating the evolution of small amounts of heat on passing through the transformation point.

SUMMARY.

1. The precautions to be observed in the preparation of the alloy are long heating, the use of silica-free crucibles and molds, casting in hot molds, annealing to the upper limit of transformation with subsequent quenching.

2. The magnetic examination shows the favorable effect of annealing at the upper limit of transformation, and the unfavorable effect of annealing at the lower limit. The transformation temperature depends upon the composition.

3. Photographic examination shows the close dependence of the magnetic properties upon the crystalline structure, and indicates that the white crystals in the photographs shown probably contain molecular groups which are capable of becoming magnetic under proper conditions of temperature.

In conclusion I wish to extend my very sincere thanks to all members of the teaching staff at the Ryerson Physical Laboratory for many courtesies and numerous helpful suggestions during the progress of these experiments which were carried out there.

UNIVERSITY OF UTAH,
July 20, 1910.

EXPERIMENTS IN IMPACT EXCITATION.

By George W. Nasmyth.

I. The Characteristics of Short Arcs Between Metal Electrodes.

§ 1. *The Development of Impact Excitation and the Short Spark Generators.*

Impact Excitation.—The year 1906 marks the beginning of the history of "impact excitation" (Stosserregung) as a method of producing high frequency electric oscillations of considerable power which are only slightly damped. In October of that year Wien[1] published a brief account of his experiments "On the Intensity of the Two Waves in Coupled Transmitters," in which he found that for small spark lengths of about 0.15 mm., a third maximum appears between the maxima of the two waves usually met with in coupled circuits. This third maximum is higher than the other two, and the shape of the curve indicates that the damping of the corresponding oscillations must be very small. Its frequency corresponds to the natural frequency of the antenna, or secondary of the coupled circuits, whereas the frequencies of the two ordinary component waves are respectively greater and less than this natural frequency. According to the theory of impact excitation, the appearance of the third wave is due to the rapid recovery of the resistance of short gaps, so that the oscillations in the primary circuit are extinguished after they have given up the greater part of their energy to the secondary circuit. The oscillations in the secondary then continue as if it were an isolated circuit, with its own natural frequency and damping factor. The electric oscillations excited by "impact" correspond, therefore, to the vibrations of a pendulum which has been started by a blow, while the ordinary

[1]Max Wien, "Ueber die Intensitaet der beiden Schwingungen eines gekoppelten Senders, "Verhandlung der Deutschen Physikalischen Gesellschaft, Vol. 8, 20, pp. 486–9, Oct. 30, 1906. See also Science Abstracts, Vol. 9, p. 633, no. 2076, 1906.

oscillations correspond to the vibrations of one of two coupled pendulums.

Lepel's Generator.—In the same year Lepel[1] began his work on the discharge between metal electrodes, and in November and December, 1906, invented a simple apparatus, using large iron electrodes separated by a film of oil, or Venetian turpentine. As early as 1890 and 1892 Elihu Thomson had succeeded in producing a type of discharge intermediate between the spark and the arc, using metal electrodes, but was unable to obtain either constancy of action or a sufficiently powerful oscillatory current for practical purposes. These difficulties were overcome by the two essential features in Lepel's device, the parallelism of the surfaces of the electrodes, thus making it possible for the discharge to take place at different points of the surface without altering the length of the path, and by the exclusion of air. Lepel later replaced the oil between the plates by mica, which was found unsuitable because it became conducting when heated, and then by one or two sheets of paper, which was found to answer every purpose. The iron electrodes were replaced by copper, either electrolytically pure or silver plated, and still later the negative electrode, when direct current was used, was made of brass or an especially dense bronze. By September, 1907, Lepel's apparatus had been so perfected that he was able to transmit messages and musical tones from Slough to Scheveningen, 160 miles, using an E.M.F. of 440 volts and 1.5 amperes of direct current.

Von Arco's "Quenched Spark."—The first public announcement of any of the short spark methods of generating oscillations was made by von Arco[2] in April, 1909. The Telefunken Company had experimented with Lepel's apparatus early in 1907, but finding it unsatisfactory in its form at that time, proceeded to develop its own system. The gap at present used by the Telefunken Company

[1]The best descriptions of Baron von Lepel's system and apparatus are to be found in The Electrician (London), Vol. 63, pp. 142, 157, 174, 345, 376, 1909; Vol. 64, pp. 153, 386, 1909–10. Abstracts from his German patent no. 24,757, filed August 20, 1907, are given in Vol. 63, p. 374, 1909.

[2]The Electrician, Vol. 63, p. 89, "A New System of Wireless Telegraphy used by the Telefunken Company," by Count Arco, April 30, 1909. See also pp. 332, 370, 461 and 720. For the relation and comparison of the Lepel and Arco systems, see also Vol. 63, pp. 228, 325, 617, 661; Vol. 64, pp. 726, 768 and 947.

differs from Lepel's gap in the use of a mica ring instead of paper, a groove being cut in the electrodes at the inner edge of the mica to prevent the discharge occurring at that place. The distance between the electrodes is about 0.25 mm., and several gaps are used in series to increase the power. The electrodes are provided with flanges to assist in radiating the heat. The secondary or antenna circuit is closely coupled to the primary so that the energy of the spark discharge is quickly absorbed. The company has given the name "quenched spark" (Loeschfunken) to this form of excitation, which is identical in principle with Wien's Stosserregung. Using an alternating current at a frequency of about 2,000 cycles the sparks may be made to follow each other so equally and regularly that they give out a clear musical tone, and this system is known as the "singing spark" (toenende Funken) system.

The practical and technical advantages of the new system over the older spark methods as well as over the undamped arc oscillations have been given by von Arco under twelve headings. Since most of these advantages are common to the other short spark systems, they are briefly summarized below:

1. Considerably smaller antenna may be used. This is due to the speed with which the sparks follow each other, so that greater power may be transmitted from the antenna at a smaller maximum voltage, and to the excellent characteristics of the short spark as a generator of short waves.

2. High overall efficiency. It is claimed that with the singing spark from 50 per cent. to 75 per cent. of the machine output can be changed into energy at the antenna, as contrasted with 20 per cent. for the older spark system and 10 per cent. for the arc lamp generators.

3. Adaptability for high power sending stations. No such limitations in the wave-length or difficulties in keeping the oscillations constant as arise in older arc methods present themselves.

4. Noiseless operation.

5. One wave is transmitted instead of two.

6. Small damping of wave sent out, from 0.08 to 0 025.

7. Constancy of the oscillations.

8. Large range of frequencies available, and the possibilities

of using overtones whose frequencies are four, five or even six times the fundamental.

9. Military advantages of using short waves which are absorbed before they travel a longer distance than is intended.

10. Sharp tuning due to constancy of oscillations and small damping of radiated wave. The freedom from disturbances is from 2 per cent. to 5 per cent., as contrasted with 20 per cent. to 30 per cent., which may in exceptional cases be reduced to 5 per cent. or 6 per cent., in arc lamp practice.

11. Elimination of atmospheric disturbances and individuality of musical tones.

12. Acoustic tuning of receivers which enables relays to be used for calling, etc.

Peukert's Rotating Disk Generator.—Recently Professor W. Peukert[1] has announced the invention of a short spark generator in 1906, for which a patent application was filed February, 1907, prior to either the Lepel or Telefunken Company applications. Peukert's apparatus consists essentially of two carefully surfaced metal disks held together by a spring pressing against one of them, with a filling of oil between. One disk is rotated at a constant speed of about 800 r.p.m., and oil is fed regularly at the center of the fixed disk and distributes itself in a uniform capillary layer between the plates. The frequency of the discharges depends upon the constants of the circuits, but in one test it was found to be 48,900 per second, as measured by the radiation to a revolving photographic plate from a needle point connected to a circuit coupled to the secondary. The gap efficiency was found to be as high as 60.2 per cent. in one test, with an applied E.M.F. of 615 volts; but the overall efficiency was not given. The generator may be made to give a definite pulsation to the oscillatory energy, thus producing a musical note in the telephone receiver, by dividing the disks into sectors, each alternate one consisting of insulating material. In this form it resembles Marconi's studded disk discharger. In its origin,

[1]The Electrician, Vol. 64, p. 361. See also p. 550 for an abstract of a dissertation presented to the Brunswick Technische Hochschule by Dr. A. Wasmus on Peukert's High Frequency Generator for Wireless Telegraphy on the Quenched Spark Method, and Peukert's English patent 4762 (1909).

Peukert's generator goes back to the results of Steidles' work[1] on contact between a spring and a rotating oil-covered disk against which it presses.

These three short spark generators constitute the chief means at present available for producing high frequency oscillations of the impact excitation type. The principle has opened up a new region and given the investigator of electric waves and oscillations a new tool, and its practical applications are so important in radio-telegraphy that new forms of generators and improved modifications of these present forms will undoubtedly result. Indeed, Wien[2] has recently announced that he has been able to obtain impact excitation effects with a spark gap of the usual length by including a vacuum tube in the condenser circuit. A wide tube having a pressure of 0.5 to 0.1 mm. of mercury, and two aluminium electrodes 2 to 3 cm. apart, was used. With a degree of coupling from 6 to 12 per cent. only one wave was obtained, the primary oscillations being damped out in a short time by the rapid recovery of resistance of the vacuum tube.

In principle the three spark generators have much in common, and experiments and theory dealing with any one will have a measure of value for each of the others. The author's experiments have been made on the Lepel generator. This is the simplest of the three, since it uses direct current instead of alternating, as in the case of the Telefunken generator, and it has no moving parts, as in the case of Peukert's apparatus.

Arc or Spark.—The discharge between the electrodes of all three generators is intermediate in character between the ordinary arc and spark discharges, and in the absence of exact definitions for the two terms, it is difficult to decide in which class they should be placed. From the arc point of view, Lepel's generator is a d.c. arc between metal electrodes, the Telefunken arrangement is an a.c. arc, and Peukert's generator is an arc between relatively rotating electrodes. But in general when the capacity circuit is connected the discharge of all three generators becomes discontinuous, and

[1]Elektrotechnische Zeitschrift, Vol. 26, p. 679, 1905.

[2]Max Wien, Ueber ein neue Form der Stosserregung elektrischer Schwingungen; Physikalische Zeitschrift, Vol. 11, p. 76, February 1, 1910.

corresponds to a spark gap. This condition also arises in the Poulson arc, although to a less extent. Von Arco has suggested the following definitions: "By arc excitation one might understand that method of producing oscillations by which the rate of condenser discharges is equal to or about the frequency of the oscillations; by spark excitations, that method by which this rate is considerably less." This definition makes the type of discharge depend upon the constants of the circuit, and the same generator might be an arc or a spark gap under different conditions. The author's experiments on the Lepel generator have demonstrated that in many of its general characteristics it bears a marked similarity to the Poulson arc, and for the present it will be called an arc whenever the applied voltage would be sufficient to maintain the current through the gap if the condenser circuit were disconnected.

§ 2. *Three Kinds of Oscillations.*

Besides the familiar damped discharge of the ordinary spark gap, three distinct types of arc oscillations have been recognized quite generally by investigators[1] in this field. For convenience the author has named these types after the experimenters who first produced them:

1. *Duddell Oscillations.*—The characteristic of these oscillations is that the maximum value of the condenser current is less than that of the direct current through the arc, so that the arc remains lighted. These are the true "singing arc" or "musical arc" oscillations, since the frequency is always within the audible range. The efficiency of these oscillations falls off rapidly as the frequency is increased, the upper limit being about 10,000. Although these oscillations are not available for radio-telegraphy on account of their low frequency, their discovery by Duddell[2] in 1900 marks the beginning of the development of undamped oscillations, and led to the discovery of the second type.

2. *Poulsen Oscillations.*—In these oscillations the maximum value of the condenser current is greater than that of the direct

[1]See K. Vollmer, Jahrbuch der Drahtlosen Telegraphie und Telephonie, Vol. 3, p. 119, December, 1909.

[2]W. Duddell, Journ. Inst. Elec. Engineers, Vol. 30, p. 232, 1900.

current through the arc, so that the arc is extinguished and relighted at each oscillation. In the Poulsen[1] arc, which is the Duddell arc immersed in an atmosphere of hydrogen and having one electrode of copper, water-cooled, oscillations having a frequency of a million per second or more may be obtained with good efficiency. These oscillations may also be produced by connecting several arcs in series, as Simon has demonstrated. Oscillations of this second or Poulsen type have been used extensively in radio-telephony. Since these oscillations are usually above the audible range, they can be called "singing arc oscillations" only by analogy.

3. *Wien Oscillations.*—Here the maximum value of the condenser current is so great that the arc is not only extinguished, but is relighted in the opposite sense. Then follows a series of damped oscillations through the arc of the well-known kind, until the potential difference is no longer sufficient to relight the arc. The condenser is then charged by the direct current until the arc resistance breaks down again, and another train of damped oscillations appears and disappears. These oscillations are easily produced if both electrodes are of metal and the arc length is short. These are the oscillations usually known as "Stosserregung" or "impact excitation" oscillations.[2]

It is with this third type, or Wien oscillations, that this investigation is chiefly concerned. The Duddell and Poulsen oscillations have been the subject of many interesting and important researches, but up to the present very few details of quantitative experiments have been published on the subject of the Wien oscillations or the characteristics of the new type of generators.

§ 3. *Arrangement of Experimental Apparatus.*

Besides the general working characteristics of an impact excitation generator, three characteristics are of especial interest: the form of the voltage current curves, on account of their importance in the theory of the action of apparatus; the intensity of the oscillations as a function of the arc current and the constants of the circuits, on account of its relation to the efficiency of the generator;

[1] V. Poulsen, British Patent Specification 15599 of 1903. See also Science Abstracts, Vol. 8A, p. 521.

[2] Max Wien, *l. c.*

and the influence of the discharger upon the frequency of the oscillations which it produces. In the author's experiments, on the Lepel arc, the arrangement of apparatus, as shown in Fig. 1, was designed with special reference to these three characteristics.

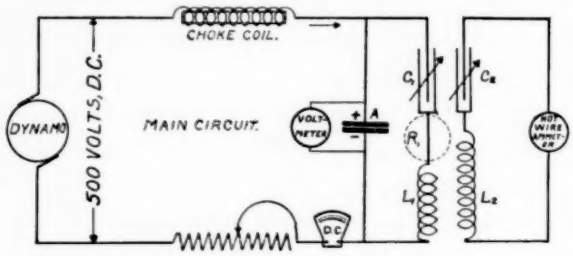


Fig. 1.

Diagram of connections.

The source of E.M.F. was a 500-volt shunt wound dynamo, direct connected to a two-phase, 900 r.p.m. induction motor. At first a Tirrell regulator was used on the dynamo, but later it was disconnected for fear that the pulsating current which resulted might introduce irregularities into the experiments. Without the regulator the voltage of the generator was found to be very steady over short intervals of a few minutes, although over intervals of a half hour or more it was subject to slow drifts of $\pm$ 20 volts. A large water rheostat made from an old oil barrel, together with two Cutler-Hammer rheostats arranged for connection in series or parallel, each having a maximum resistance of 200 ohms and a current capacity of 1.5 to 2.5 amperes, constituted the resistance in the circuit. The choke coils were two solenoids 47.5 cm. long, wound with seven layers of 192 turns each of double cotton covered copper wire 2.05 mm. in diameter. The inside diameter was 8.2 cm. and the outside 11.4 cm. The coefficient of self induction, measured by comparison with an Ayrton-Perry standard, was 0.0296 henry for each coil. In the condenser circuit, a variable number of Leyden jars, having a capacity of 0.00188 microfarad each, were connected in parallel. The inductance in the primary circuit was also varied but for most of the experiments a solenoid 20.55 cm. long, having a mean diameter of 12.85 cm. and consisting of 15 turns of stranded wire insulated and wound on a glass jar, was used. The diameter

of the wire, which was made up of 36 strands, was 0.65 cm.; the coefficient of self induction of this solenoid was 14,300 cm., and the resistance of the condenser circuit with this solenoid connected and the capacity short circuited, was only 0.15 ohms, as measured by a Wheatstone bridge.

A Weston d.c. voltmeter of the d'Arsonval galvanometer type, with a 600-volt and 150-volt scales, was connected across the arc, and a Weston millivoltmeter, with a 5-ampere shunt, was connected in series with the main circuit, as shown. The intensity of the oscillations was measured by an unshunted hot wire ammeter containing no iron and giving a maximum deflection at 7 amperes of direct current. The position of the ammeter when used for measuring the oscillations is shown by the dotted circle in the primary circuit. The expanding wire was of copper, 0.22 mm. in diameter and 9 cm. long, and the resistance of the instrument is included in the 0.15 ohms mentioned above. The hot wire ammeter was calibrated before and after reading by short circuiting the capacity and causing a direct current to flow through the hot wire ammeter and the main circuit ammeter in series.

§ 4. *The Lepel Arc.*

After experimenting with various forms of the Lepel apparatus, it was found that with flat copper plates water cooling of the electrodes was unnecessary, as the radiation to the air was large, and the generator seemed to work better, if anything, as it became heated by the discharge.

The Electrodes.—The author's first experiments were made with brass and copper plates. The results obtained when either metal was used as cathode were fairly satisfactory, but the pitting of the brass plate, due possibly to the volatilization of the zinc, was found to be a source of great annoyance and to make the oscillations inconstant by changing the arc length. Two electrodes of sheet copper ¼ inch thick and 6 inches in diameter were then obtained. These were carefully surfaced in a lathe with a sharp tool set at an acute angle, and were then rubbed with sandpaper and oil. The connecting wires were at first soldered to the copper plates, but after they had been melted off two or three times, they were fastened

to screws set into the edges of the plates. These electrodes were found very satisfactory, and Fig. 2 is from a photograph showing the appearance of the electrodes and insulating paper after they had been used almost continuously for six hours. Although the paper was burned brown and the copper discolored by the heat they were working as well at the end of the run as at the beginning, and after the bluish deposit of carbon from the burnt paper had been rubbed off with emery cloth the electrodes were ready for another test.

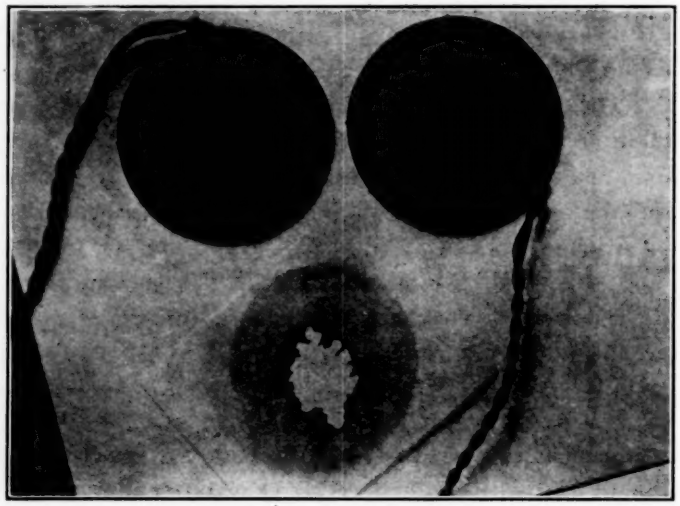


Fig. 2.

Photograph showing appearance of copper plates and paper after a six-hour run.

The oscillations are more irregular when the surfaces of the electrodes have been rubbed with emery cloth than when oil and a sandpaper block is used. When the emery is used it is probable that little points remain sticking in the copper. On the other hand, the vapor of the oil (ordinary machine lubricating oil was used) seemed to have a marked effect in steadying the arc conditions.

Very good electrodes may be made from the hard rolled copper plate used in the photo-engraving processes. The surface of this copper is very smooth and flat, and it holds its shape well on account of its hardness. If this copper sheeting is used, it is unnecessary to turn the plates to a flat surface in a lathe, an operation requiring

some skill. The plates need only be rubbed with fine pumice stone and oil, and then with a piece of wood carbon and oil, and the surface is almost perfect. Contact with the connecting wires may be made by means of a piece of tinfoil held down by a small weight.

The Insulator.—Any kind of paper seems to work well as an insulator and as a source, when disintegrated by the discharge, of the hydrogen and carbon atmosphere which the arc requires for satisfactory working. For the sake of uniformity in conditions, W.S. & B. Paragon typewriter paper in legal size sheets was used in all the quantitative experiments. In thickness this paper is very closely 0.05 mm. per sheet and the arc length was varied by increments of this amount by using a varying number of thicknesses. Mica rings were tried without success, as the discharge occurred either at the edge of the mica, or, if this were prevented by cuting a sufficiently deep groove in the plates, the discharge took place through the mica instead of across the air gap. Since there is no hydrogen atmosphere present when mica is used, the potential difference required for sparking is higher. Moreover, the insulating properties of mica disappear in large measure with rise of temperature. Water cooling is probably essential for the successful use of mica, and in addition to the groove at the edge the plates should be planed off outside the groove, so that the distance between the plates through the mica is greater than the distance through air gap.

Starting the Arc.—If a potential difference of 500 volts is applied to the electrodes of the Lepel arc when they are separated by two or three sheets of paper having a small hole in the center, the discharge will not in general take place. If the insulation of the gap can be broken down, however, the discharge will continue, the average voltmeter reading across the arc being from 37 v. upwards, according to the current, arc length, etc. To start the arc various devices may be used, the most convenient one being to short circuit the arc and then suddenly break the short circuit, thus bringing the full pressure of the inductive kick of the choke coils to bear on the gap. To break the short circuit suddenly, the author has used the following simple form of oil switch. One electrode of the arc is connected to a brass binding post having a flat top. Insulating oil poured on

this will be held by surface tension to a depth of a millimeter or more. Then a piece of brass having a wooden handle and connected to the other electrode is touched to the top of the binding post through the oil, making a short circuit across the gap. The circuit is then broken in the oil, resulting in a high potential difference across the gap which is usually sufficient to start the discharge. Theory shows that the inductive kick is greatest when the resistance in the main circuit is least, *i. e.*, when a large current flowing through the short circuit is suddenly interrupted.

If the edge of the hole in the paper has been charred, by a match or some other means, the discharge will start as soon as the potential difference is applied. After the discharge has been stopped and the electrodes taken apart, it will usually start automatically if the same paper is used when the apparatus is put together again. If the paper is charred too much, either a short circuit will result, giving a voltmeter reading of from 20 to 40 volts, or an inactive stage of the arc sets in which does not produce oscillations although the voltmeter gives a steady deflection of about 325 volts and a current of two or more amperes flows through the arc. To start the oscillations again after this inactive stage has set in, either the plates must be rubbed clean or the charred part of the paper must be moved to a new place on the plates.

Arcs in Series and Parallel.—As in the case of the Poulsen arc the Lepel generator may be made to give increased power by connecting several arcs in series. By starting the arcs one at a time separately and then connecting them together in series, the author has been able to make as many as three arcs run on 500 volts impressed E.M.F. This was only possible at relatively large currents, however; at smaller currents the arcs would go out and it would be necessary to start from the beginning again. The power obtained in the oscillations with three arcs in series was considerably less than three times the power delivered by one arc.

A better way to obtain increased power at a given impressed E.M.F. is to connect two arcs in parallel, each with its own choke coil and resistance in series. If the two cathodes (or anodes) are connected together, and the capacity and inductance of the condenser circuit connected to the two anodes (or cathodes) the same

potential difference will be required as for one arc alone and the two arcs will add their characteristics, doubling the power available for the oscillations. The critical resistance in the condenser circuit at which oscillations can be obtained is equal to the sum of the absolute values of the negative slopes of the volts-amperes characteristic curves for the two arcs, and is therefore about double the resistance which can be used with a single arc.

The method of generating oscillations by connecting arcs in parallel in this way was discovered by the author in 1907 in attempting to apply the principle of Vreeland's mercury vapor magnetic field oscillator to the arc, and the advantages of the connection were set forth under the title "An Improved Form of the Duddell Singing Arc."[1] Later the attention of the author was called by Mr. Duddell to a lecture given in England before the Institution of Electrical Engineers in 1900, in which practically the same principle had been used. The author had overlooked the reference to the earlier work, and is glad to take this opportunity of acknowledging the priority of Duddell in discovering the method of generating oscillations by connecting arcs in parallel.

§ 5. *The Volts-Ampères Characteristic Curves.*

The form of the characteristic curves between the voltage as measured by a d.c. voltmeter across the arc and the current through the arc is of considerable theoretical and practical importance. According to the theory of the Duddell oscillations, in order that oscillations may be produced, the curve must have a negative slope and its value, $-dV/dA$, must be greater than the resistance of the shunt circuit. From its similarity to the Duddell and Poulsen arcs, it might be inferred that a similar law would hold for the Lepel arc. Moreover, the shape of the characteristic curve has an important bearing upon the question of the variation of frequency in the oscillations produced by the arc. One of the first problems in the author's experiments, therefore, was to determine the form of these curves.

The characteristic curve for an arc length of 0.15 mm. when the arc is generating oscillations is shown in Fig. 3. Three sheets

[1] PHYS. REV., Vol. 28, p. 459, 1909.

of paper were used, and the capacity and inductance of the oscillation circuit are given. The points plotted are from tests made on two successive days, each extending over the whole range of the curve. For currents much larger than 4 amperes the arc be-

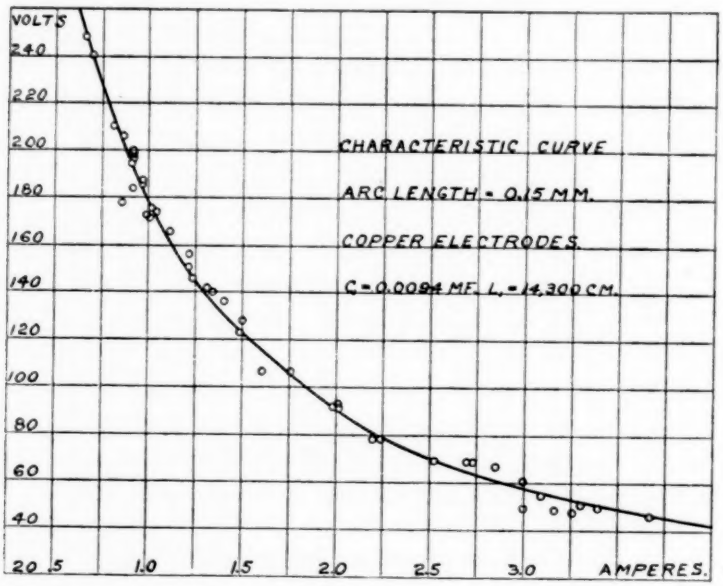


Fig. 3.

Characteristic volts-amperes curve for the Lepel arc with oscillations.

comes inactive and the oscillations cease, probably on account of the flatness of the curve for large currents. For currents less than 0.7 ampere it is difficult to obtain steady conditions on account of the steepness of the curve. Fig. 3 shows therefore the range over which steady oscillations can be obtained with an arc length of 0.15 mm.

The readings of the d.c. instruments represented in Fig. 3 are of course average or integrated values. Theory shows that with the large inductance of the choke coils in the main circuit the current varies but little during the charge and discharge of the condensers. The fluctuations of the voltage may be very great, however, and the voltmeter reading, expressed mathematically, is

$$V = \frac{1}{t}\int_0^t v\,dt,$$

where v is the instantaneous voltage and is integrated over the complete cycle of charge and discharge. To obtain the complete history of the arc current and voltage during the cycle it would be necessary to employ an oscillograph.

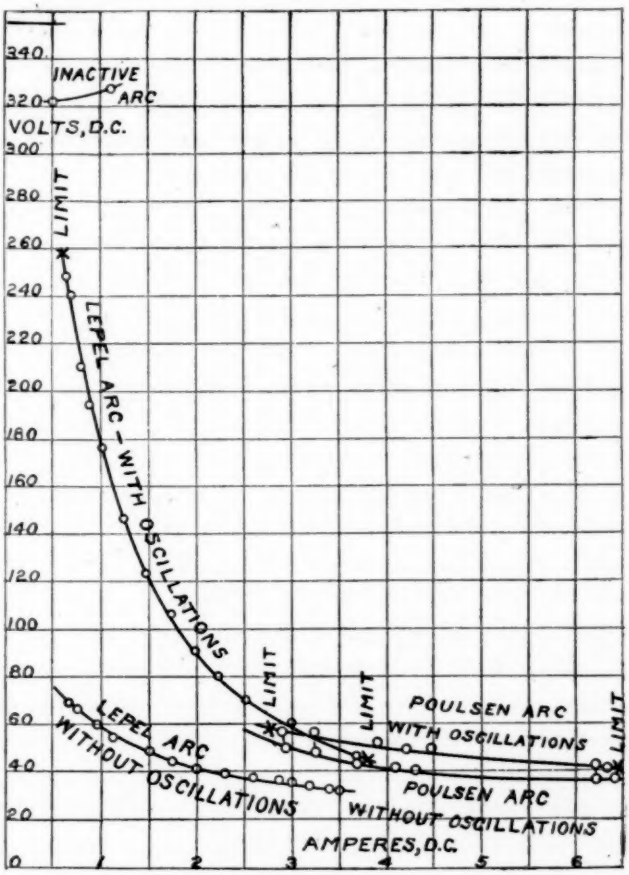


Fig. 4.

Comparison of Lepel and Poulsen arc characteristics.

The relation of the Lepel arc characteristics to those of the Poulsen arc are shown in Fig. 4. The upper and lower curves for the Poulsen arc are taken from an earlier paper[1] by the author and represent the characteristics for an arc between a water-cooled

[1]The Frequency of the Singing Arc, PHYS. REV., Vol. 27, p. 126, 1908.

copper anode and a graphite cathode in an atmosphere of illuminating gas when the switch in the oscillation circuit is open and closed, respectively. The points for the corresponding curve for the Lepel arc "with oscillations" are taken from Fig. 3; the lower curve for the Lepel arc gives the corresponding characteristic when the condenser circuit is disconnected.

One reason for the greater effectiveness of the Lepel arc is due to the steepness of the characteristic in the region of small currents in which it operates. Even at larger currents, however, where the two generators can be directly compared, the Lepel characteristic seems to be much steeper than that for the Poulsen arc. The separation of the two curves for the Lepel arc is also seen to be much greater than that for the Poulsen arc. In experiments with the Poulsen arc, the author has found that the oscillations cannot be started unless the resistance of the condenser circuit is less than the smaller of the negative slopes of the characteristics, but that when once started the resistance can be increased until it is but slightly less than the negative slope of the steeper characteristic. If the same conditions hold for the Lepel arc, the resistance would still have to be quite small in order to have the oscillations start, on account of the small value of the slope of the lower characteristic, but once started, it should be possible to increase the resistance through a large range before it becomes equal to the negative slope of the characteristic "with oscillations."

The limits of the current between which oscillations could be obtained in the author's experiments are indicated by crosses in Fig. 3. At small currents the characteristic of the Lepel arc becomes so steep that the oscillations are very irregular, and although oscillations have been obtained at currents less than 0.5 amperes, they were transient or very unsteady. At larger currents the characteristic becomes too flat, but by decreasing the resistance of the shunt circuit still further oscillations could be obtained with currents larger than 4 amperes. The product of the difference of the voltages of the two characteristics by the corresponding amperes may be taken as a measure of the power converted into oscillations. Since the characteristic "without oscillations" varies but little for the different arc lengths, a comparison of the characteristics "with

oscillations" will furnish a means of finding the arc length and current which will transform most power into oscillations and give the greater efficiency. It will be found from the three following figures that with with the author's apparatus the maximum power and efficiency are obtained at an arc length of 0.2 mm. and with a current between 1.0 and 1.5 amperes.

An inactive state of the arc which results sometimes when it is extinguished and started again, or when the paper is charred too much, is represented by the short curve between 320 and 330 volts. When this inactive stage sets in, the plates must be taken apart and the surfaces cleaned before steady oscillations can be again obtained. A condition which sometimes exists when the oscillation circuit is opened is represented by the horizontal line at 356 volts. This

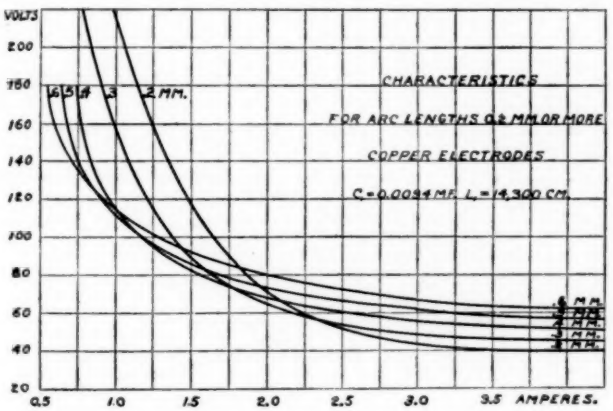


Fig. 5.

corresponds to the minimum sparking potential between copper electrodes, and seems to be accompanied by a small leakage current. When the oscillation circuit is again connected the oscillations do not always start, but the voltage remains at 356 no matter how small a resistance is placed in series with the arc.

In attempting to find the change in the characteristic curve when the arc length was varied, apparently discordant results were obtained. For large currents the voltage increased with increasing arc length, as in the case of the Poulsen arc, but for small currents the voltage sometimes increased and sometimes decreased with

increase of arc length. It was then decided to make a systematic exploration of the whole characteristic field, taking a hundred or more observations at each arc length under different conditions and at different times, and drawing a smooth curve through the observations, as in Fig. 3. The results of these experiments are shown in Figs. 5 and 6, representing more than a thousand single observations. The observations for each arc length were drawn on a separate sheet, and when a transparent sheet of cross-section paper was placed over these and the curves traced one after another, the cause of the apparent discrepancies became clear.

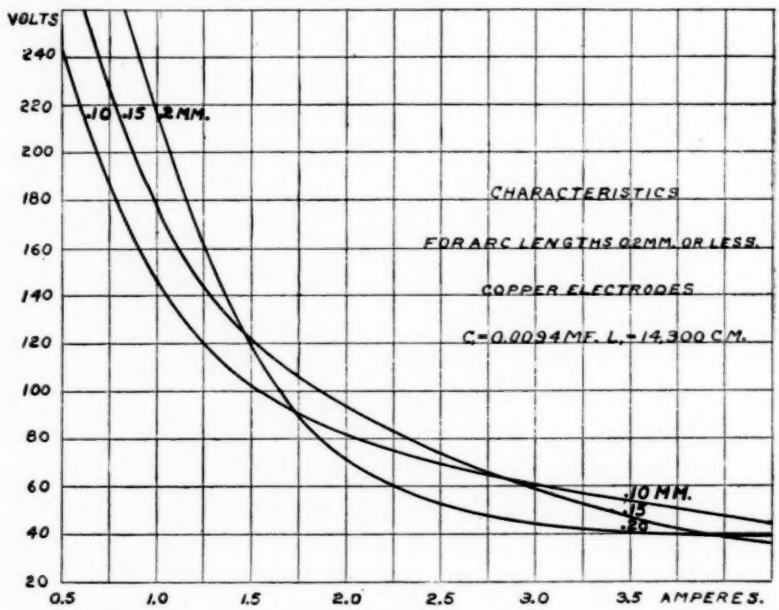


Fig. 6.

Lepel arc characteristics for different arc-lengths.

Although at large currents the curves tend to lie one above the other in the order of the corresponding arc length, at low currents the case is far different. To avoid confusion the characteristic curves have been plotted in two groups, the common characteristic for the 0.2 mm. arc length serving as a standard of reference. It is evident from these curves that for small currents (*e.g.*, one ampere) as the arc length is increased from 0.1 to 0.2 mm., the voltage increases;

then as the arc length is increased to 0.5 mm. the voltage falls off rapidly at first, then more slowly, and begins to rise again as the length is increased to 0.6 mm. If cross-sections of the curves are taken in this way at constant currents, and the potential difference across the arc plotted against the arc length, the family of curves shown in Fig. 7 is obtained.

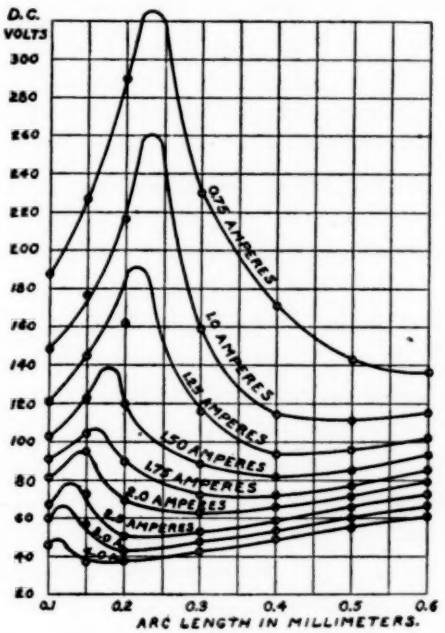


Fig. 7.

P.d. across arc for constant current and varying arc length.

The form of the curves suggested a resonance phenomenon, and tests were at once made to determine whether the effect was a true one corresponding to something inherent in the short spark form of excitation, or a false effect, due to some peculiarity in the measuring instruments. The substitution of another voltmeter, which gave the same readings at all points which were tried, showed that the phenomenon was not due to any resonance with the natural period of the voltmeter pointer. Moreover, the high resistance of the voltmeter, amounting to about 60,000 ohms on the 600-volt scale, precluded the possibility of resonant oscillations through the voltmeter.

The measurement of the resistance in series with the arc at various currents and arc lengths furnished another test which seemed to be conclusive. In all the tests that were made, it was found that, within the limits of the errors of observation, the resistance of the circuit was the same, whether it was found from the ratio of the open circuit, E.M.F., E, to the current I, through the main circuit when the arc was short circuited, or from the formula,

$$E - V = RI, \tag{1}$$

where V is the voltmeter reading across the arc. The resistance in the main circuit corresponding to any current and arc length or voltage can be determined, therefore, to a close approximation from the curves of Fig. 7, if E is taken as 500 volts.

The characteristics from which the curves of Fig. 7 are taken were drawn as smooth curves in Fig. 5 and 6, all small deviations being taken as due to errors of observation. From an inspection of the points plotted in Fig. 3, however, it is apparent that there are systematic deviations in the neighborhood of 3 amperes, which would accentuate the maxima and minima in Fig. 7 slightly. A reexamination of all the original curves plotted showed that a similar effect ran through all the observations. In general these deviations are less than those shown at about 2.8 and 3.2 amperes in Fig. 3, and if they had been taken into account in plotting the final result would have been changed but little. At the longer arc lengths some small deviations gave rise to the suspicion that the minor maxima which are apparently just beyond the range of Fig. 7 came into this range at larger currents, but the effects were too small to make this certain.

The first clue to the cause of the phenomenon shown in Fig. 7 was obtained accidentally. Part of the variable resistance in the main circuit consisted of german silver coils, 61 in all, each about 61 cm. long, 1.5 cm. mean diameter and having about 2 turns per cm. of wire 1.13 mm. in diameter. The inductance of this resistance was about 330,000 cm., and it was found that the voltage reading for the same current and arc length varied when this resistance was replaced by the non-inductive rheostat. Thus, with an arc length of 0.2 mm. and arc current of 2.25 amperes, the voltmeter reading

rose from 59 volts to 64 volts when the inductive resistance was replaced by the rheostat, the intensity of the oscillations increasing with the voltage.

§ 6. *Variation of Voltage with the Capacity of the Arc.*

In seeking the reason for the variation of the arc voltage with the inductance of the main circuit, the relative times of charge and discharge of the condensers seemed to offer the most satisfactory basis for explanation. But the relative times of charge and discharge depend even more directly upon the capacity of the condensers, and experiments were made at once to determine if the capacity had any effect upon the arc voltage. It was found that increasing the capacity of the shunt circuit by adding more Leyden jars increased the intensity of oscillations, while the voltage sometimes increased and sometimes decreased. The d.c. ammeter reading would increase as the capacity was added, usually, and the resistance of the main circuit would have to be increased in order to bring it back to the same reading, but sometimes this effect would be reversed also.

These observations led to the suspicion that the curious variations in the arc voltage as the arc-length was increased might be due to the change in the capacity of the arc as the distance between the plates was varied. A rough computation, using 1 as the dielectric constant of the paper and gas between the plates, showed that the capacity of the arc varied between rather wide limits, from 0.0016 mfd. at 0.10 mm. arc-length to 0.00023 mfd. at 0.70 mm. Accordingly, a variable air condenser was connected directly across the arc, and the values of the arc voltage and oscillation current were read as the capacity in parallel with the arc was varied. The arc-length used was 0.25 mm., and the d.c. ammeter reading was maintained constant at 2.5 amperes by varying the resistance in the main circuit. The results are given in Table I. and graphically in Fig. 8.

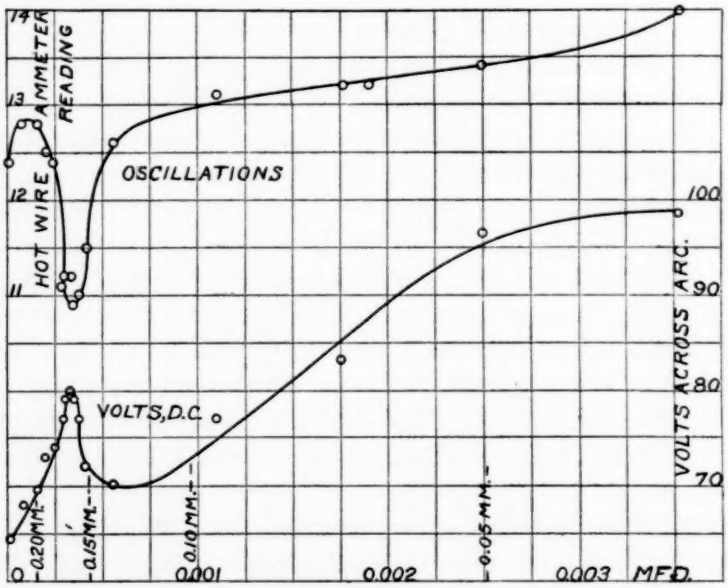
In Fig. 8 the variable capacity in parallel with the arc is plotted as abscissa, with the d.c. voltage across the arc and the corresponding intensity of the oscillations indicated by a hot wire ammeter as ordinates. The capacities corresponding to arc-lengths of 0.05,

TABLE I.

Change of Arc Voltage and Oscillation Intensity with Arc Capacity.

Capacity in Parallel.	Volts, d. c.	Oscillation Current.	Resistance in Series.
0.000015 mfd.	64.5	12.4	176 ohms.
0.000075	68	12.8	174
0.000156	69.5	12.8	171
0.000195	73	12.5	171
0.000240	74	12.4	171
0.000285	77	11.1	166
0.000300	79	11.2	166
0.000320	80	11.2	166
0.000345	79	10.9	166
0.000375	77	11.0	168.5
0.000420	72	11.5	168.5
0.000560	70	12.6	174
0.00110	77	13.1	166
0.00176	83	13.2	158
0.00190	87	13.2	158
0.00248	96	13.4	155
0.00353	98	14.0	154

D.c. ammeter reading in main circuit maintained constant at 2.50 amperes by changing resistance. 500 volts open circuit.



Capacity across arc.

Fig. 8.

Effect of arc capacity on arc voltage and oscillations.

0.10, 0.15 and 0.20 mm. have been marked, and the left-hand boundary of the figure, with no capacity in parallel, corresponds of course to the arc-length of 0.25 mm. actually used. The resistances in series with the arc have not been plotted, but it is evident from Table I. that the resistance curve is approximately the reciprocal of the voltage curve. At the voltage maximum the resistance is a minimum, agreeing with the oscillations curve. At larger capacities, however, the resistance decreases with increasing voltage, whereas the oscillations increase. In all cases the value of the resistance observed agrees closely with the value obtained by subtracting the potential difference across the arc from 500 volts and dividing by 2.5 amperes, according to equation (1).

It is apparent that the voltage curve with varying arc capacity corresponds qualitatively at least with the voltage curve for varying arc length at 2.5 amperes shown in Fig. 7. The maximum in the voltage in Fig. 7 occurs at an arc-length less than 0.15 mm., while in Fig. 8 the maximum occurs at a capacity equivalent to an arc-length slightly more than 0.15 mm., as calculated. The discrepancy is due in part to the manner in which the plates forming the arc electrodes were arranged in the two experiments. In the earlier experiments which gave the data for the curves of Fig. 7 the plates could not be adjusted so as to completely overlap, on account of the projection of the screws which held the connecting wires. In the later experiments when the importance of the capacity of the arc had become apparent they were made to overlap more completely, thus increasing the capacity, and making an arc length of about 0.25 mm. in the later experiments equivalent to an arc length of about 0.20 mm. in Fig. 7. This would shift the maximum in Fig. 7 into the region of shorter arc lengths and tend to bring the two sets of curves into agreement.

The inductance of the wires which connected the variable air condensers in parallel with the arc would decrease the effect of their capacity and give a correction which would also shift the maximum in the right direction. This inductance was small, however, as the area enclosed by the connecting wires was not more than 3×25 sq. cm. The small correction due to a dielectric constant greater than one for the paper and gas between the plates

would make the equivalent capacity for each arc length slightly greater and would tend to neutralize in part the effects of the other two corrections.

The curve for the intensity of the oscillations in Fig. 8 shows that the oscillations are a minimum when the voltage is a maximum, *i. e.*, when the equivalent arc length is about 0.15 mm. The readings of the hot wire ammeter given in the table and shown graphically in the curve are in scale divisions of the instrument. The divisions were unequally spaced so as to give a simple multiplying factor when the ammeter was used unshunted, so that the readings may be taken as proportional to the oscillation current, even when used with a shunt, if, as in this experiment, the frequency is practically constant. In attempting to calibrate the instrument later by comparison with a less sensitive unshunted ammeter, the expanding wire was burned out. From the readings obtained however, and from observations of the intensity of the oscillations made under similar conditions later, the multiplying factor may be taken as about 0.4, so that a reading of 14 scale divisions indicated about 5.6 amperes.

As a further test of the effect of capacity on the arc voltage, a run was made with a constant d.c. ammeter reading of 2.0 amperes. The large upper electrode was replaced in this experiment with a small copper disc 3.85 cm. in diameter and an arc length of 0.15 mm. was used, giving a capacity of only 0.000069 mfd. as compared with 0.00108 mfd. for the larger plate with the same arc-length. On varying the capacity of the air condensers in parallel with the arc, it was found that the maximum in the voltage had shifted to a smaller capacity, corresponding to a longer arc length of slightly more than 0.2 mm. This is in agreement with the shift of the maxima to longer arc lengths with smaller currents shown in Fig. 7.

In this experiment it was possible to reduce the capacity of the arc to smaller values than had been obtained before, and it was found that the voltage decreased from a maximum of 100 volts at a capacity equivalent to about 0.2 mm. to a minimum of 80 volts at 0.4 mm. equivalent, and then increased to another maximum of 85 volts at a capacity 0.9 mm. equivalent, falling off to 75 volts

when there was no capacity in parallel with the small electrode. The second maximum observed evidently lies just beyond the range of Fig. 7. A minimum of 4.7 amperes was observed in the oscillations when the voltage was at the first maximum corresponding to 0.2 mm., although the minimum in the curve for the oscillations was not so sharp as that shown in Fig. 8. There was no minimum in the oscillations corresponding to the smaller second maximum in the voltage at 0.9 mm. equivalent, but instead a maximum of 5.3 amperes, the reason for which is unknown.

At 1.5 amperes the maximum in the voltage shifted over to the region of still smaller capacities, corresponding to a longer arc length between 0.20 and 0.25 mm., and the maximum increased to 113 volts. Both the shift and the increase in the maximum are in agreement with Fig. 7.

The experiments with capacity in parallel with the arc show therefore that the maxima observed in the voltage in Fig. 7 are due chiefly to the changing capacity of the arc itself, as the arc length is varied, and that corresponding to these maxima in the voltage there are minima in the oscillations produced by the arc. This is in agreement with the hypothesis advanced to account for the maxima in the voltage-arc length curves. When the time required for the main current to charge the condensers is long compared with the time of discharge, the effective value of the oscillations should be small and the average value of the d.c. voltmeter reading large. The reason for the minima in the oscillations and the corresponding maxima in the voltage together with the importance of these minima in the production of impact excitation effects will be considered more fully in the later sections which deal especially with the intensity of the oscillations. A brief summary of the explanation, however, is given in section 7.

From the connection which has been established between the maxima in the voltages and the minima in the oscillations it is possible to predict what would be the effect upon the curves in Fig. 7 if the capacity or inductance of the condenser circuit were varied. It will be shown in the sections dealing with the intensity of the oscillations that the d.c. ammeter reading at which the minima in the oscillations occur increases with increasing capacity

and with decreasing inductance in the condenser circuit. This is the same effect as shown in Fig. 7, where the corresponding maxima in the voltage moves into the region of smaller arc-length and larger arc capacity as the d.c. ammeter reading is increased. We may consider, then, that the capacities of the condensers and of the arc are in parallel, and that the effective capacity of the condensers is decreased by the inductance in series with them. If the curves shown in Fig. 7 were determined with a larger capacity or a smaller inductance in the shunt circuit, therefore, the capacity of the arc would have to be reduced in order to have the same capacity for the whole system, and the maxima would move into the region of longer arc-lengths.

The reason for the increase of voltage observed when the inductance of the main circuit was decreased becomes clear when we consider the effect upon the relative times of charge and discharge. With a smaller inductance in the main circuit the generator current falls off more during the condenser charge, and the time of charge is made longer. But this is the same effect as that produced by an increase of capacity. Decreasing the inductance of the main circuit should have the same effect as increasing the capacity or decreasing the arc length, therefore, and from Fig. 7 it is apparent that at 0.2 mm. and about 2.25 amperes a decrease of arc-length should raise the voltage. This is in agreement with the effect observed. A change of inductance in the main circuit should produce an increase of voltage if made on one side of the maximum and a decrease if made on the other, and this effect has also been observed in the author's experiments, always in the direction which agrees with the theory.

§ 7. *Explanation of Maxima and Minima.*

At small capacities the condensers will charge up quickly, the number of discharges per second will be great, and the sparking potential will be low, since the gas will remain ionized to a large extent. The intensity of the oscillations, as measured by a hot wire ammeter, will be large, and the average d.c. voltmeter reading low, partly on account of the low sparking potential, and partly because the charging time, when the voltmeter reading is obtained,

is relatively small compared with the discharging time, when the voltmeter indication should be relatively small.

At large capacities, on the other hand, the quantity of energy liberated at each discharge is large, the trains of oscillations will last a long time, and their effective value will be large even though the number of discharges per second is relatively small. A large reading of the hot wire ammeter should therefore be obtained. But the resistance of the arc will be small while the large current is flowing through it and the time of each discharge is large compared with the time of charge. In this case also, then, the average voltmeter reading will be small.

Between these limiting cases a low value of the oscillations may result from a low value of the group frequency, due to high sparking potential, and a low value of effective oscillation current, due to small capacity. The time of charge will be relatively great and the time of discharge relatively small, giving a large value of the average voltmeter reading. The minimum in the oscillations should correspond with a maximum in the voltage, therefore, and this effect is observed in Fig. 8.

The reason for the shift of the maxima into the region of larger arc capacities as the current is increased is clear from this explanation. If the direct current from the generator is increased, the time required to charge the condensers will be decreased. This is the same effect as would be produced by a decrease of capacity. To neutralize this effect the actual capacity would have to be increased, thus restoring things to the same condition. In other words as the charging current is increased the maxima should move over into the region of larger capacities or shorter arc-lengths, and this is the effect found experimentally.

The combination of all the independent and dependent variables, capacity, sparking potential, times of charge and discharge and group frequency, may give rise to several maxima and minima when the capacity is varied and the current is maintained constant. A complete discussion of these can only be obtained with the aid of the equations of charge and discharge after the form of the sparking potential as a function of the effective arc current, the capacity and the other constants of the circuit are known.

The rapidity with which the oscillations are damped out will evidently be a function of the maximum amplitude with which they start, depending upon the primary capacity and inductance, and of the sparking potential and group frequency. The minimum value of the oscillations corresponds both to relatively small initial amplitude and high sparking potential and therefore to strong quenching. The points of the maximum voltage readings in Fig. 7, which correspond to minima and strong quenching in the oscillations, represent conditions especially favorable for the production of impact excitation effects.

§ 8. *Variation of Sparking Potential with Arc Current.*

In order to test the assumption that the sparking potential required to break down the insulation increased as the arc current was diminished, a Braun cathode ray oscillograph was connected across the arc, as shown in Fig. 9, so that the maximum deflection of the ray by the electromagnetic field measured the maximum instantaneous or sparking potential across the arc.

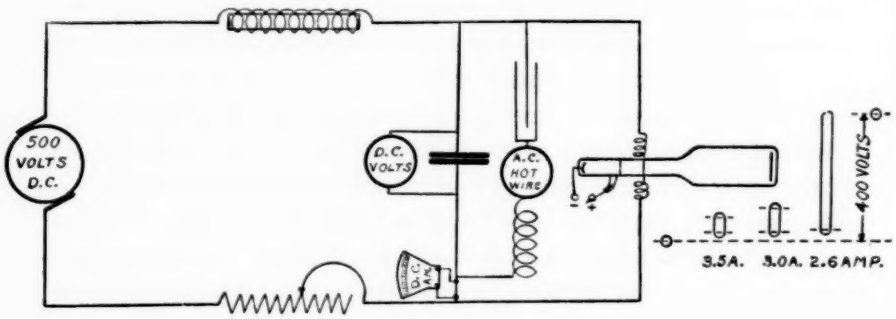


Fig. 9.

Determination of sparking potential by Braun oscillograph.

The oscillograph was calibrated by noting the deflection produced by different applied voltages before the arc was started, and it was found that the potential difference measured by the voltmeter across the arc was directly proportional to the deflection of the fluorescent spot on the cross-sectioned screen. It was found that a good deflection of 21 scale divisions could be produced by one half an ampere, and a resistance of 450 ohms was placed in

series with the deflecting field before it was connected across the arc. On account of the appreciable current taken by the deflecting field, the five ampere shunt which converted the millivoltmeter into a d.c. ammeter was connected so that only the arc current passed through it.

At the right of Fig. 9 is shown the appearance of the fluorescent spot under the different conditions of the experiment. With no potential difference across the arc the fluorescent spot was a small circle, as shown at the left. When the current of 3.5 amperes d.c. was sent through the arc and the oscillations started, the circle spread out into a band of light with bright spots at the ends and a less bright region between. The lowest position of the spot of light corresponded to 29 volts across the arc, and highest position to a maximum potential of 68 volts. The voltmeter reading was between these limits, 52.5 volts, and the intensity of the oscillations was about 5.4 amperes.

When the d.c. ammeter reading was reduced to 3.0 amperes, the bright discs spread still farther apart, the lower one rising slightly to 31 volts, and upper limit increasing to a maximum potential of 104 volts. The voltmeter reading was 68 volts, and the intensity of the oscillations 5.6 amperes.

When the current was reduced still further to 2.6 amperes d.c., bringing it into the region of the oscillation minimum and voltage maximum, the lower disk was raised to a point corresponding to 34 volts, but the well defined upper disk disappeared. A bright region extended up to something more than 100 volts, and beyond this frequent long streamers or tails reached up to 400 volts or more. The voltmeter reading was about 76 volts, occasionally running up to 80 volts, and the intensity of the oscillations fell off to 5.0 amperes. Finally the arc went out, and the impressed potential difference across the plates was found to be 400 volts.

No oscillations could be obtained at smaller currents, nor could the arc be kept in operation. Apparently the shunt of 450 ohms across the arc prevented the high sparking potentials which were necessary at smaller currents from being attained. An arc-length of 0.15 mm. was used in all cases, and the capacity and inductance of the oscillatory circuit were 0.0169 mfd. and 14,400 cm. respect-

ively. The experiments were repeated with a capacity of 0.0132 mfd. and gave very nearly the same results for the large currents, while at 2.7 amperes the maximum voltage as shown by the streamers on the fluorescent screen was about 300 volts.

The experiment shows therefore, that the maximum or sparking potential increases as the arc current is decreased and is accordingly in agreement with the theory advanced. Apparently at the point where the oscillations are a minimum there is a cumulative effect which increases the sparking potential more for a given decrease of direct arc current than at other points. This is due undoubtedly to the effect of the oscillations themselves upon the sparking potential. The lowest potential across the arc also increases slowly as the direct current is increased, and apparently agrees fairly well with the curve marked "without oscillations" in Fig. 4, the voltages being slightly lower in this case because the oscillations lower the resistance of the arc.

All the phenomena observed with the cathode ray oscillograph pointed to a form of voltage oscillation curves very similar to those observed by Barkhausen[1] using the Poulsen arc. He employed an electric field to give a deflection proportional to the arc voltage, and a magnetic field to give a deflection at right angles proportional to the condenser current. His curves show large increases of the sparking potential as the arc current is decreased, and smaller increases of the lower limit of potential, in agreement with the author's experiments. Unfortunately, no plates for making an electric deflecting field were available inside the Braun tube used by the author. It is evident, however, that the phenomena observed in one dimension in the author's experiments on the Lepel arc are very closely related to the boot shaped diagrams drawn out in two dimensions in Barkhausen's curves.

§ 9. *Variation of Arc Current with Arc Length.*

If horizontal sections are taken through the family of curves shown in Figs. 5 and 6 the variation of the current through the arc, as read by the d.c. ammeter, is found to have maximum and mini-

[1]H. Barkhausen, "Die Erzeugung dauernder Schwingungen durch den Lichtbogen," Jahrbuch der drahtlosen Telegraphie und Telephonie, Vol. I., p. 243, 1907.

mum values as the arc length is increased while the voltage across the arc is maintained constant. This is chiefly an effect due to the capacity of the arc, and is explained in the same way as the variation in voltage at constant current was explained, the two phenomena being complementary. The curves obtained in this way are shown in Fig. 10.

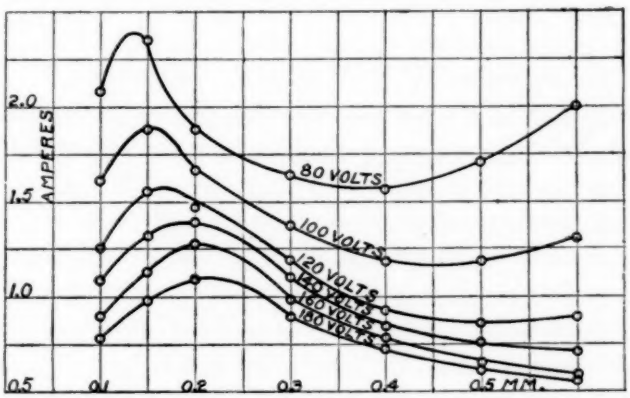


Fig. 10.

Variation of arc current with arc length at constant voltage.

It is apparent from a comparison of Figs. 7 and 10 that the maxima for the volts at constant amperes correspond to the maxima for the amperes at constant volts, all the quantities being measured with d.c. instrument. In both sets of curves the maxima move into the regions of longer arc-lengths as the voltage is increased or the current reduced.

An alternative interpretation may be given to the curves in Fig. 7 and 10 if we assume that the voltage across the arc depends not merely upon the direct current through the arc, but rather upon the effective arc current, or the square root of the sum of the squares of the direct current and the oscillatory current. According to this interpretation, when the oscillations are at a minimum, corresponding to a critical value of the capacity of the arc, the effective current through the arc would be small, and the voltage across the arc would rise to a maximum even though the d.c. ammeter reading is kept constant. The maxima in Fig. 10 correspond to the minima oscillations, and it is apparent, from the

point of view of effective current values, why the direct current must be increased in order to keep the voltage constant.

According to this interpretation, if the effective arc current, as measured by a hot wire ammeter, were maintained constant, the voltage across the arc should remain constant when the capacity across the arc is varied, and should change but slightly when the arc length is varied.

§ 10. *Analogous Effects Observed by Duddell and Others.*

Investigators who have used the ordinary spark gap as a means of producing high frequency oscillations have long been familiar with a phenomenon similar to that shown by the curves in Fig. 10. For a given constant applied voltage at the high tension transformer or induction coil, there is a definite spark length which will give a maximum current in all the circuits. It is possible that this effect is due in part to the influence of the capacity of the spark, but it is probable that the variation of the sparking voltage and spark resistance with the spark length plays a much more important than in the case of the short arc between large electrodes.

A more marked effect has been observed by Duddell[1] in the secondary current of an induction coil when a mercury interrupter was used to make and break the primary current. With a small spark gap between two aluminium points about 1.2 mm. apart in the secondary, the current measured by a hot wire ammeter rose to a maximum about double the value observed when the secondary spark gap was short circuited. The maximum in Duddell's curve with currents as ordinates and spark lengths as abscissas is sharper than that shown in any of the curves in Fig. 10, but the general characteristics are the same. Duddell's curve has also the same features of a maximum followed by a minimum and then an increase of current as far as the observations are continued shown by the upper curves in Fig. 10. The influence of a change in the shape of the electrodes in Duddell's experiment and the variations in the oscillations when the capacity of the secondary circuit was changed by touching an insulated metal plate to various points of it indicate that the effect was due in part at least to the capacity of the spark

[1]W. Duddell, The Electrician, Vol. 61, p. 796, 1908. See also discussion, p. 134.

gap. It is probable, however, that the resistance of the spark gap in Duddell's experiment plays a relatively more important part than in the phenomena of the Lepel arc.

Summary of Results.

For electrodes of the short arc oscillation generator copper was found to be most satisfactory material, and with plates not more than one quarter inch thick water cooling was found to be unnecessary. The kind of paper used for separating the plates is immaterial, but much difficulty attends the use of mica. Charring the paper and breaking a short circuit across the arc in oil is the most effective method of starting the arc when only a low voltage is available. Connecting arcs in parallel, each with its own choke coil and inductance, gives double power for the same applied voltage, and has other advantages over series connection.

The Lepel arc has a falling characteristic much steeper than those of the Duddell or Poulsen arcs and operates on smaller currents. The separation of the two characteristics obtained with and without oscillations is much greater for the Lepel arc than for the others. The characteristics for increasing arc-lengths lie one above the other at large currents, but at small currents the order is reversed. This is found to be due to marked maxima in the voltage across the arc which occur at smaller arc lengths as the current is increased.

The maxima in the voltage are due indirectly to the variation in the arc capacity, which is quite large on account of the small distance between the plates which form the electrodes. The maxima in the voltage are caused by corresponding minima in the oscillations produced by the arc. The capacity of the arc and of the condensers are in parallel, but the inductance in series with the condensers partly neutralizes the effect of their capacity and makes the capacity of the arc more important. Decreasing the inductance of the main circuit has the same effect on the voltage as increasing the capacity of the arc.

The minima in the oscillations and corresponding maxima in the voltage across the arc occur because for certain values of sparking, potential, arc current, capacity and inductance, the time of discharge is a minimum compared with the time of charge. The minima in

the oscillations furnish conditions especially favorable for strong quenching of the oscillation and for impact excitation effects.

Experiments with Braun cathode ray tube show that the maximum instantaneous or sparking potential for the arc increases as the arc current is decreased. The sparking potential is especially high in the region of the minima in the oscillations.

The direct current through the arc required to maintain the voltage constant as the arc-length is varied is found to have a maximum where the oscillations are a minimum. This is chiefly a capacity effect also, but is similar to certain phenomena in spark gap excitation in which the variation in the resistance of the arc plays a more important part.

In the succeeding sections on the intensity and frequency of the oscillations, it will be shown that the minima in the oscillations occur at larger values of the direct current through the arc as the capacity in the shunt circuit is increased or the inductance diminished, and that the intensity of the oscillations themselves increase. It will also be shown that the frequency of the oscillations increases with the arc current and decreases with the arc length, and that the formula derived by the author for the frequency of the singing arc holds true also for the frequency of the oscillations produced by the new short arcs between metal electrodes.

PHYSICAL LABORATORY,
CORNELL UNIVERSITY,
June 25, 1910.

EXPERIMENTS IN IMPACT EXCITATION.

By George W. Nasmyth.

II. The Intensity of the Lepel Arc Oscillations as a Function of the Arc Current, Capacity and Inductance.

IN the preceding sections on "The Characteristics of the Short Arc Metal Electrode Generators" the apparatus used and the results of the experiments on the relation between the voltage and current of the Lepel arc, consisting of two copper plates separated by a few sheets of paper, were described. It was found that the Lepel generator resembles the arc more closely than the spark gap, and has, in common with the Duddell and Poulsen arcs, a falling voltage-ampere characteristic. Certain curious maxima in the d.c. voltage across the arc were observed as the arc length was varied at constant current, and the cause of these was finally traced to the influence of the capacity of the arc itself. It was found that these maxima in the voltage are accompanied by corresponding minima in the intensity of the oscillations. In the following sections the effect of the variation of the arc current and the capacity of the condenser circuit upon the intensity of the oscillations will be investigated, and later the question of the frequency will be taken up. For the present the connections remain as shown in Fig. 1, the Lepel arc being connected to a 500-volt d.c. generator through a choke coil and variable resistance, with an oscillation circuit containing capacity, inductance and a thermoammeter, in shunt.

§ 11. *The Intensity of the Oscillations.*

Two striking phenomena meet the observer who sets out to investigate the intensity of the oscillations in the condenser circuit. First, the alternating current, as measured by an unshunted hot wire ammeter in the condenser circuit, is two or three times greater than the direct current measured by an ammeter in the main circuit.

Second, if the direct current in the main circuit is varied, the intensity of the oscillations passes through a well-defined minimum. The value of the direct current at which this minimum in the oscillations occurs depends on the constants of the circuit, increasing when the capacity is increased, and decreasing when the inductance is increased. The first characteristic indicates that these oscillations belong to the third class of "Wien" or "impact" oscillations; the second characteristic has interesting consequences in the theory of the relation of the intensity of the oscillations to the other factors of the circuit.

Inasmuch as the frequency of the oscillations varies with the current in the main circuit, the difficulties of calibration at varying frequencies made it impossible to use any kind of an ammeter with a shunt. Accordingly a special ammeter was constructed without the use of iron, in which the entire current passed through a small copper wire, 0.22 mm. in diameter, and about 9.5 cm. long. This ammeter was connected in the oscillation circuit, as shown by the dotted lines in Fig. 1 of the preceding article (see p. 76), and calibrated before and after each set of observations by comparison with the direct current ammeter in the main circuit.

The results of the experiments on the variation in the intensity of the oscillations with the arc current are given in Table II. and graphically in Fig. 11. The readings of the d.c. ammeter in the main circuit, called for brevity arc amperes, were varied by changing the resistance in the main circuit and the corresponding oscillation amperes as indicated by the hot wire ammeter in the condenser circuit were noted. The corresponding readings of the d.c. voltmeter connected to the two electrodes of the Lepel arc are also given.

Each curve in Fig. 11 corresponds to a definite capacity in the oscillation circuit, one Leyden jar representing a capacity of 0.00188 microfarad. The same inductance, 14,400 cm., was used for the nine curves, so that the frequency range was from 324,000 with 9 jars capacity, to nearly a million with one jar.

In each of the curves in Fig. 11 the oscillations pass through a minimum, well-defined in the curves for the larger capacities, less so at small capacities. These minima move over into the region of larger arc currents as the capacity is increased, following ap-

TABLE II.

Variation of Oscillation Intensity with Arc Current and Primary Capacity. Arc Length 0.15 mm. $L_1 = 14{,}400$ cm. Copper electrodes six inches diam.

Arc Amperes D.C.	Oscillation Amperes.	Arc Volts D.C.
Capacity, 1 Jar = 0.00188 mfd.		
0.50	1.00	——
0.70	1.20	176
1.00	1.40	108
1.15	1.70	94
1.25	1.70	82
1.34	1.86	84
1.60	2.00	72*
1.70	1.81	64
1.75	1.65	63
1.85	1.65	62
1.90	1.63	62
2.00	1.65	61.5
2.20	1.86	60
2.40	2.03	57
2.50	2.06	57
Capacity, 2 Jars = 0.00376 mfd.		
0.76	2.40	——
1.03	2.20	——
1.50	2.32	76
1.55 min.	2.28	71
1.60	2.32	70
1.70	2.43	69
1.80	2.49	68
1.90	2.64	66
2.00	2.76	64
2.50	2.34	63*
2.65	2.30	59*
Capacity, 3 Jars = 0.00564 mfd.		
1.30	3.00	——
1.41 min.	2.80	91
1.45	2.90	88
2.20	3.03	64
2.30	3.05	63
2.40	3.10	62
2.50	3.21	62
2.60	3.28	61
Capacity, 4 Jars = 0.00752 mfd.		
1.45	3.85	96
1.60	3.25	82
1.70	3.17	79
1.75 min.	3.12	76.5
1.80	3.14	75.5
2.00	3.25	70
2.05	3.30	69
2.25	3.41	67
2.50	3.48	62
2.71	3.52	56
2.75	3.53	56
2.90	3.54	54.7
3.01	3.69	53
3.20	3.90	52
3.30	3.86	52
3.36	3.90	52
3.42	3.95	52
3.50	3.80	51.5
3.63	3.59	48
3.72	3.69	49
3.80	3.55	47
4.00	3.70	46
Capacity, 5 Jars = 0.00940 mfd.		
1.08	5.56	——
1.30	5.15	146
1.48	5.00	126
1.60	4.92	116
1.70	4.62	104
1.80	4.27	88
2.00	3.82	73
2.15	3.80	70
2.25	3.57	66*
2.50	3.77	65
2.75	3.86	61
3.00	3.90	53*
3.26	4.01	50
3.50	4.12	50
Capacity, 6 Jars = 0.01128 mfd.		
1.45	6.23	——
1.52	6.05	138
1.63	6.05	128
2.00	5.70	97
2.23	5.00	82
2.47 min.	4.04	68
2.54	4.09	——
2.67	4.25	64
2.75	4.35	63
2.94	4.62	59
3.00	4.76	58
3.25	4.76	56
3.50	4.83	53
3.75	4.72	49
4.00	4.83	47
Capacity, 7 Jars = 0.01316 mfd.		
2.35	6.00	
2.50	5.83	
2.55	5.60	
2.75	5.24	
2.83	5.20	
2.97 min.	4.92	
3.02	4.98	
3.20	5.14	
Capacity, 8 Jars = 0.01504 mfd.		
2.35	6.28	
2.75	6.00	
3.02	5.60	
3.05	5.50	
3.19	5.28	
3.29 min.	5.10	
3.45	5.35	
3.50	5.24	
Capacity, 9 Jars = 0.0169 mfd.		
2.82	6.1	72
3.18	5.9	—
3.43	5.6	—
3.51 min.	5.2	50
3.80	5.6	50

Points starred * are not plotted, to avoid confusion in the figure.

parently a straight line law. The descent to the minima is much steeper from the region of smaller arc currents, and in some of the curves a maximum followed by another minimum can be seen in the region of larger arc currents.

It was shown in § 7 that there are maxima in the voltage across the arc corresponding to minima in the oscillations as the capacity

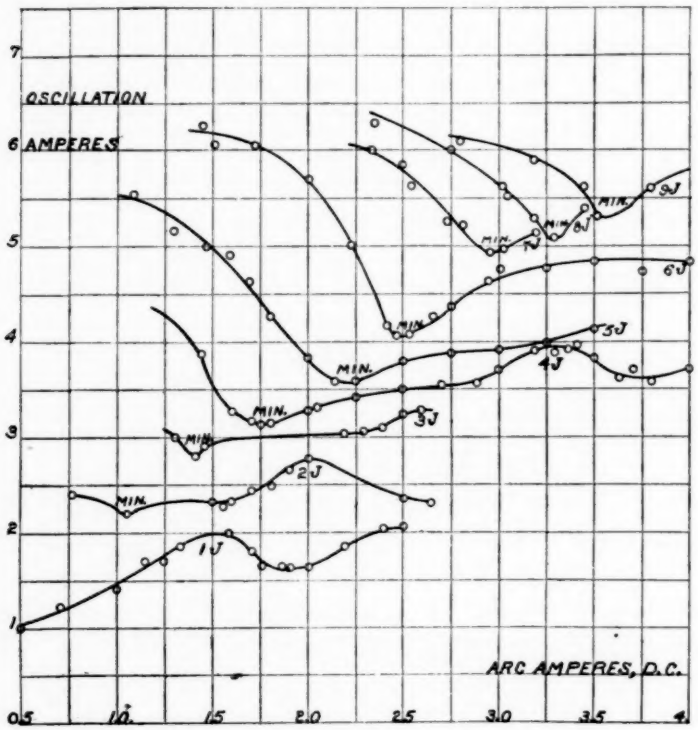


Fig. 11.

Variation in intensity of oscillations with arc current at constant capacities.

of the arc is varied at constant arc current. Moreover in § 5 it was shown that as the capacity of the arc was increased the maxima in the voltage moved into the region of larger arc currents.

This is evidently another phase of the phenomena shown by the shifting of the minima to larger arc currents as the capacity is increased, in Fig. 11, and furnishes additional evidence that the capacity of the arc itself must be considered as connected in parallel

with the capacity of the condenser-circuit as far as the effect upon the intensity of the oscillations is concerned.

The effect of the primary capacity upon the arc voltage is shown in Fig. 12, from the data of Table II. Besides the increase of voltage with added capacity there is also a change of the form and slope of the curves, the increase of voltage for small currents being greater than that for large currents. There is some indication of the maxima in the voltage corresponding to the minima in the

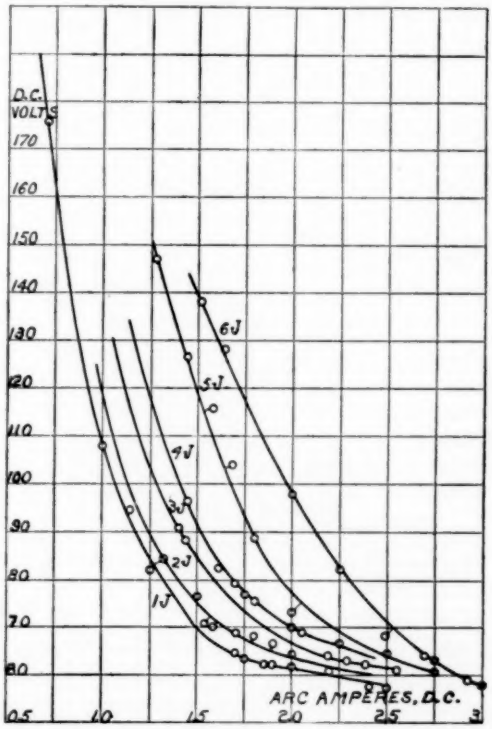


Fig. 12.
Increase of arc voltage with primary capacity.

oscillations of Fig. 11, but not enough points are available to bring out the humps of the curves clearly.

The influence of the minima in the oscillation intensity upon the frequency of the oscillations will be discussed in §§ 17–19. The bearing of the effect of capacity in increasing the oscillation intensity and changing the slope of the voltage-ampere characteristics upon the question of the frequency will appear in § 20.

In Table III. arc currents at which the minima in the oscillations in Fig. 11 occur, together with the intensity of the oscillations corresponding, are tabulated. Similar data are given for larger inductances with the addition of the d.c. voltmeter reading across the arc. In the data for 46,400 cm., the readings when a non-inductive resistance of one ohm was added to the condenser circuit are also given. The effect of resistance seems to be the same as that of capacity in increasing the arc voltage and the arc current at which the oscillation minima are found, but the change is too small to be conclusive.

TABLE III.

Shift of Oscillation Minima with Capacity and Inductance. Arc Length 0.15 *mm*

Primary Capacity Leyden Jars. Capacity, Microfarads.	3 0.00564	4 0.00752	5 0.00940	6 0.01128	7 0.01316	8 0.01504	9 0.0169
Primary Inductance $L_1 = 14{,}400$ cm.							
Arc Current for Minimum Oscillations	1.33	1.84	2.12	2.34	3.02		
Minimum Oscillation Amperes	3.1	3.6	4.06	4.10	4.98		
Primary Inductance $L_1 = 46{,}400$ cm.							
Arc Current for Minimum Oscillations	1.22	1.60	1.85	2.20	2.60	2.95	
Same, one ohm added	1.32	1.68	2.00				
Minimum Oscillation Amperes	3.08	3.23	3.42	3.51	3.90	4.08	
Same, one ohm added	3.04	3.27	3.51				
Arc Volts at Minimum Oscillations	64	56	46	41	41	—	
Same, one ohm added	76	64	64.2				
Primary Inductance $L_1 = 176{,}000$ cm.							
Arc Current for Minimum Oscillations		1.45	1.68	1.98	2.25	2.65	2.90
Minimum Oscillation Amperes		—	1.49	1.77	1.99	2.46	2.95
Arc Volts at Minimum Oscillations		—	45	44	42.5	42	44
Primary Inductance $L_1 = 327{,}500$ cm. Lower Minima.							
Arc Current for Minimum Oscillations		1.02	1.22	1.40	1.68	1.83	1.95
Minimum Oscillation Amperes		1.57	1.82	1.90	2.03	2.19	2.35
Arc Volts at Minimum Oscillations		76	66	58	53.5	49.5	47.5

In Fig. 13 the arc currents at which the minima in the oscillations occur are plotted as ordinates with the corresponding capacities as abscissas. The resulting curves are seen to be straight lines. As the inductance in the oscillation circuit is increased, the slope of these lines is seen to decrease, at first rapidly, then more slowly. The arc current for minimum oscillations is apparently some inverse function of the inductance, and directly proportional to the capacity.

At small inductances traces of a second minimum were observed at smaller currents, and at large inductances these secondary minima became more prominent than the others. The lowest curve shows

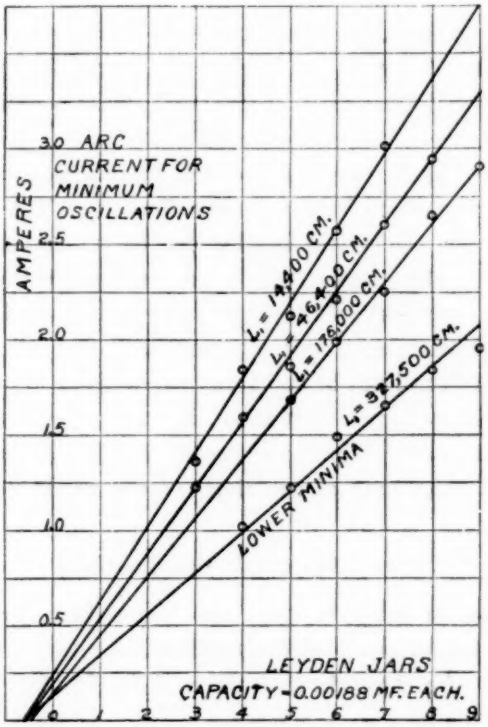


Fig. 13.

Shift of oscillation minima to larger arc currents with increasing capacity and decreasing inductance.

that this secondary minimum follows the same straight line law as the primary minima.

§ 12. *Influence of the Capacity of the Arc.*

The straight lines of Fig. 13 all give an x intercept corresponding to the capacity of the arc itself, considered as a condenser. The capacity of the arc has been computed from the dimensions and distance apart of the plates to be about two thirds of one of the Leyden jars. The mean value of the x intercepts in Fig. 13 by least squares was found to be 0.54 Leyden jars, equivalent to 0.01

microfarad. In the experiments the plates never overlapped completely, on account of the projection of the screws and connecting wires, and it was observed that when the overlapping was less complete, as in the experiments at 176,000 cm. of inductance, the x intercept corresponding to the capacity of the arc was smaller.

The capacity of the arc is added to the capacity of the condenser circuit as far as the intensity of the oscillations is concerned. But for the frequency of the oscillations the author's experiments, to be described later, show that the arc acts merely as a resistance and that its capacity effect does not enter directly. This is only to be expected, as the arc could hardly act as a condenser when its insulation is broken down and a current is flowing through it. An important corollary of these two observations is that the Lepel arc may be available as a source of very high frequency oscillations whose intensity shall not be too greatly decreased. In other words, with an arc whose capacity is large, it may be possible to produce electric waves shorter than one meter, having a mean intensity much greater than that of the short waves produced by a Hertz oscillator.

§ 13. *Theoretical Considerations.*

We can obtain some insight into the reason for the minima observed in the intensity of the oscillations and shown in Fig. 11 with the aid of a formula first derived by M. La Rosa[1] for the maximum value of the oscillatory current. If we write down the energy relations for the condenser circuit for the instant of sparking and for the instant when the condenser current is a maximum, we have

$$\frac{Li_{\max.}^2}{2} = \frac{LI^2}{2} + \frac{Ce^2}{2}$$

where i is the condenser and I the generator current and e the sparking potential of the gap.

This equation states that the energy stored in the self induction ($\frac{1}{2}Li_{\max.}^2$) at the instant when the current in the condenser is a maximum is equal to the energy contained in the self induction ($\frac{1}{2}Li^2$) at the instant of sparking increased by the energy given to

[1] La Rosa, Nuovo Cimento, Vol. 7, 5, 1904.

the condenser ($\frac{1}{2}Ce^2$) during the charging time T_1. Solved for the maximum condenser current, the equation becomes

$$i_{max.} = \sqrt{(I^2 + Ce^2/L)}. \quad (5)$$

The four assumptions under which the formula holds have been summarized by Vollmer as follows:

1. At the instant of sparking the condenser current $i = I$, the generator current.

2. The damping loss due to the resistance of the condenser circuit is negligible.

3. The energy produced in the condenser circuit on account of the falling characteristic of the arc during the discharge time T_2 is negligible. (In the Duddell oscillations this is the main source of energy.)

4. The energy $Ce_b^2/2$, stored in the condenser at the instant that the condenser current is a maximum is negligible. (e_b is the potential difference across the arc during the maximum discharge.)

In order that the formula shall hold for the short spark generators it is necessary to assume also:

5. The energy stored in the capacity of the spark gap itself is negligible.

Theory shows that the assumption 1 is permissible since for a sufficiently large choke coil in the main circuit the changes in the generator current are very small.

The errors introduced by assumptions 2 and 3 tend to neutralize each other, since the amounts of energy neglected in the two cases have opposite signs. Only the difference in these amounts of enegy will have an influence and this difference will usually be small.

Assumption 4 is unnecessary, as Vollmer has shown, if we use, instead of e^2, the difference of the squares of the sparking potential e and the potential difference across the arc during discharge, e_b.

The author's experiments have shown that the capacity of the arc cannot be neglected in the short spark generators, but as a first approximation we may treat the equation as it stands.

The experiments with the Braun tube described in § 8 have shown that the sparking potential decreases as the generator current I is

increased. Barkhausen[1] has found the same effect in the Poulsen oscillations. The sparking potential also increases with the arc length, as might be expected. The data available are not sufficiently accurate or extended to determine the law of the variation of sparking potential with the arc current, but if we assume the simplest relation, that the sparking potential is inversely proportional to the generator current, we have

$$e^2 = k/I^2,$$

the proportionality factor k being a function of the arc length. For small variations in the arc length is it probable that k may be considered a constant, as the variation in k will be small in comparison with the total sparking potential even at very small lengths. Using this value of e, the approximate formula (5) becomes

$$i_{max.} = \sqrt{(I^2 + Ck/LI^2)}. \tag{6}$$

At large values of the generator current I, the first term under the radical will be of importance, and the second term small. For small values of the generator current, the second term will be important, and the first term small. Under the limiting conditions of very large or very small currents I, therefore, the condenser current maximum, $i_{max.}$ will be large, but at intermediate values the condenser current will have a minumim in its initial maximum value and in its corresponding effective value. This is in agreement with the experiments of the author.

We can find the value of the current for which the oscillations will be a minimum by equating the differential $di_{max.}/dI$ to zero. The condition for a minimum is

$$I^4 = k\frac{C}{L}, \tag{7}$$

so that the critical current for minimum oscillations should be a function of the capacity and inductance at constant arc length. This also is in agreement so far with the author's experimental results. The experiments show that the critical current is directly proportional to C (Fig. 13) instead of to the fourth root, however.

[1]H. Barkhausen, Jahrbuch der Drahtlosen Telegraphie und Telephonie, Vol. 1, p. 251.

The difference may be due in part to the influence of capacity on the relations of the maximum and effective values of the condenser current, and in part to the influence of the frequency, which is a function of the capacity on the sparking potential. The indirect effect of an increase in the capacity in lowering the sparking potential (through the influence of the duration and intensity of the oscillatory current) would also modify the relation between the capacity and arc current for minimum oscillations.

The capacity of the arc is in parallel with the capacity of the condensers and the divided circuit may give rise to the two minima, observed in the oscillations. The effective capacity of the condenser branch of the divided circuit is reduced by the inductance in series, however, and with a large inductance in the condenser circuit the capacity of the arc becomes more important. This is probably the reason why the second minima become more important than the first at the large inductance of 327,500 cm. as shown in Fig. 13.

Impact Excitation.—The bearing of the minima in the value of the effective and initial maximum condenser current upon the problem of impact excitation is apparent. It is evident that the oscillations will be most quickly damped out when their initial value is least. The average intensity of the oscillations will be least also in this case. To secure the most favorable conditions for impact excitation, therefore, the arc current or arc length should be adjusted to give a minimum in the intensity of the oscillations. If the arc current is varied by means of a rheostat in the main circuit at constant arc length, capacity and inductance, the desired minimum can easily be found with the aid of a hot wire ammeter.

Summary.

The intensity of the oscillations in the condenser circuit of the Lepel arc is in general two or three times greater than the direct current supplied to the arc by the generator.

The intensity of the oscillations increases with the capacity very rapidly at small arc currents, more slowly at larger currents. Inductance and resistance decrease the intensity of the oscillations.

As the arc current is increased at constant capacity the oscillations

fall rapidly to a minimum and then increase slowly, passing through a maximum to a secondary minimum.

As the capacity is increased or the inductance decreased, the minima and maxima in the oscillations shift into the region of larger arc currents. A linear relation exists between the arc current for minimum oscillations and the capacity. The range through which oscillations can be obtained shifts with the minima.

The explanation for the minima in the oscillations is found in the effects of the energy stored at the instant the gap breaks down. The energy stored in the inductance is large for large arc currents, while the energy stored in the capacity is large, on account of the increased sparking potential, at small arc currents, giving a minimum at intermediate arc currents.

The condition of minimum oscillations is most favorable for strong quenching and impact excitation.

The d.c. voltage across the arc increases with the capacity of the condenser circuit. The increase is most rapid at small arc currents, so that the form of the voltage-current characteristics is changed by the capacity in parallel.

The capacity of the arc is added, as if it formed a parallel circuit to the capacity of the condenser circuit, for the intensity of the oscillations, but not for the frequency.

STUDIES IN THERMO-LUMINESCENCE.

IV. The Distribution of Light in the Luminescence Spectrum of Sidot Blende.[1]

By C. A. Pierce.

Introductory.

THE characteristic decay curve of phosphorescent substances is well known. If $1 \div \sqrt{I}$ is plotted as ordinates with t as abscissæ, the decay curve appears to consist of two straight lines, of different slopes, which gradually merge into one another. One of the early explanations of the decay of phosphorescence was that by H. Becquerel, who assumed that phosphorescence light was due to molecular vibrations which were set up by the exciting light. It was shown by him that, if the damping forces were proportional to the square of the molecular speed, the decay curve, in the case of a substance which had but one band in its phosphorescence spectrum, would be of the form[2]

$$I = \frac{1}{(a + bt)^2}.$$

For substances which have more than one band, Becquerel proposed for the law of decay of the total light,

$$I = \Sigma \frac{1}{(a + bt)^2}.$$

Using $1 \div \sqrt{I}$ and t as coördinates, the first law gives a straight line curve, while the second law gives a more complicated curve.

Working with a single substance, Sidot blende, Nichols and Merritt showed[3] that the spectrum did not change its form during the first three or four seconds of decay. The measurements were made

[1] This is a continuation of a preceding article which appeared in the Physical Review, Vol. XXX., No. 6, June, 1910, p. 663.

[2] Comptes Rendus, Vol. 113, p. 618, 1891.

[3] Phys. Rev., Vol. XXI., No. 4, Oct., 1905, p. 247.

upon the one broad bright band of the spectrum. If there were other bands in the spectrum, they decayed too rapidly to be measured.

Later the same authors studied[1] the decay of the same substance at different wave-lengths and found the decay in each case to follow the straight line law for the first ten seconds, although the slopes of the several lines were different, indicating a difference in the rapidity of decay.

Still later the same authors studied[2] the decay of the total band and found the curve to consist of two straight lines, of different slopes, which gradually merged into one another.

In an article[3] on thermo-luminescence, the author of the present article showed that Becquerel's law for the decay of light consisting of two bands represented the decay of the total band, as found by Nichols and Merritt, as closely as could be expected. By assuming that a change of temperature affected the decay of one of the hypothetical bands more than the other, the data on decay curves at different temperatures were accurately explained by the same law. In another article[4] by the present writer, the same law was used to explain the so-called hysteresis effect, which is due to the previous history of the phosphorescent substance.

Since the typical decay curve is always more complex than a single straight line, it is necessary to assume more than one band taking part in the decay in order to apply Becquerel's law. This led to the suggestion in the article above that, if there were always two bands, one might be due to some secondary effect. The assumption of more than one band is in contradiction to the data obtained by Nichols and Merritt, which indicated that the band did not change its shape with decay, but they did not study the band late enough in the decay to be certain that it did not change at the time the decay curve exhibited the typical bending. Their data upon decay curves corresponding to different wave-lengths offer no evidence for or against the existence of two bands, for while the straight line decay found at each wave-length seems to contra-

[1] PHYS. REV., Vol. XXII., No. 5, May, 1906, p. 279.
[2] PHYS. REV., Vol. XXIII., No. 1, July, 1906, p. 37.
[3] PHYS. REV., Vol. XXVI., No. 4, April, 1908, p. 312.
[4] PHYS. REV., Vol. XXVI., No. 6, June, 1908, p. 454.

ct this view, the different slopes of the straight lines are in agreement with it. The symmetrical smooth-sided band showed in the article preceding this would indicate that, if it were composed of two bands, they must be nearly of equal size.

More recently, in a theoretical article,[1] E. Merritt has considered the effect of different factors upon the form of the decay curve. It was shown by him that absorption of light by the phosphorescent material and irregularities in the distribution of the active component of the powder would explain part of the deviation of the typical decay curve from a straight line, but he decided that the two effects were not of sufficient moment to explain all of the deviation. Complex molecular grouping would account for the whole change. The author stated, however, that no data were available which definitely contradicted Becquerel's law, although several objections could be raised to it.

The present article and the one preceding it were undertaken to provide data with which to prove or disprove the two-band theory of phosphorescence decay. The work is based on the assumption that the typical decay curve is represented accurately by the summation of two straight-line decay curves. It has been suggested that the decay curve in its earliest parts is not in accordance with such an assumption, but recent data[2] by C. A. Zeller would seem to definitely prove the fallacy of these suggestions. The straight-line component parts of the typical decay curve differ widely in slope. Hence, on the assumption of two bands, most of the light before the bend in the curve is due to the band corresponding to the steeper straight line[3]; at the bend, the light is due more or less equally to both bands; and after the bend, the light is due mostly to the second band. With a method available for studying the light distribution before and after the bend, the two-band explanation would be proved or disproved depending on whether a change was or was not found in the distribution of light.

A method was developed in the first of these two articles with which the energy distribution of fluorescence light could be

[1] PHYS. REV., Vol. XXVII., No. 5, Nov., 1908, p. 367.
[2] PHYS. REV., Vol. XXXI., No. 4, Oct., 1910, p. 367.
[3] Fig. 3, p. 316, PHYS. REV., Vol. XXVI., No. 4, April, 1908.

studied by photographic means. This method was developed in such a manner as to avoid the assumption that a constant product of intensity of light at any wave-length times the length of exposure would give a constant density on the photographic negative, an assumption which was found not to hold even approximately.

The results of the first part of the work showed that the energy distribution of the fluorescence light of the substance used consisted of one prominent, symmetrical, smooth-sided band with a maximum at about $\mu = 0.55$. The band extended, approximately, from $\mu = 0.46$ to $\mu = 0.60$. Furthermore, the energy distribution immediately after excitation is the same as in the fluorescence light.

The present article is concerned with the light distribution before and after the bend in the decay curve and also with the effect of different temperatures and the effect of infra-radiation upon the fluorescence spectrum.

EXPERIMENTAL.

The method employed to photograph the decaying band of phosphorescence was based on the assumption that the conditions and phenomena could be reproduced indefinitely, a fact practically proven true for the substance under investigation. The phosphorescent powder, except in the case of Fig. 49, was emanations pulver, called by the writer Sidot blende, the same sample of powder having been used in the investigations previously published.

The apparatus was practically that used in the previous investigation, except electrically operated shutters were substituted to excite the powder, to expose the plate and to kill off the remaining phosphorescence with infra-radiations before repeating the excitation. With this apparatus the decay curve could be photographed between any two points time and time again until an impression had been made on the photographic plate. Since, at best, the necessary exposure was very long, varying from a few hours to a much longer time, no attempt was made to deduce the energy distribution, but the photographic spectra were compared with each other, the principle weight being attached to the position of the maximum of the band. The necessary attention was given to obtain negatives of about the same average density and of not too great density so

that no complications could result from widely different or complete chemical change of the films at any wave-length. With these precautions, negatives were obtained which showed definite maxima and the results could be repeated as many times as desired.

The distribution of denseness on the photographic film was measured, at first, with a photometer, as in the previous article, but this method was soon abandoned because of the eye strain induced by comparing very faint fields of light. The apparatus which was substituted consisted of a brightly illuminated slit placed before a very sensitive thermo-couple system. The photographic

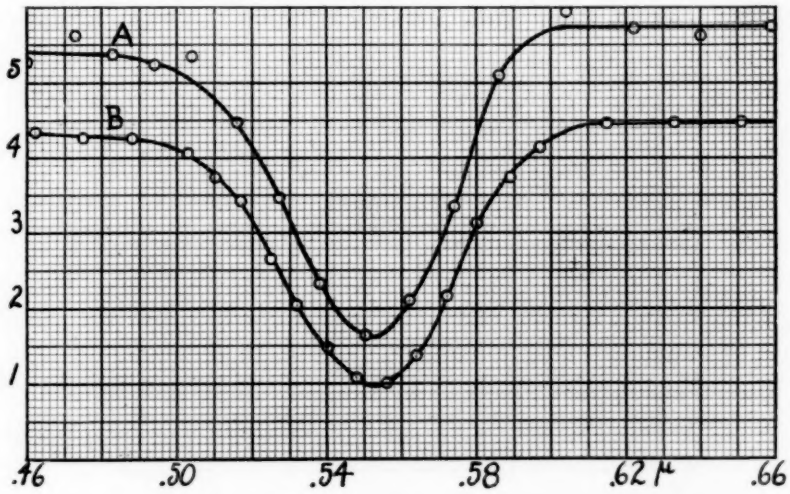


Fig. 47.

plate was pushed past the slit by means of a screw calibrated in wave-lengths. Since the deflection of the galvanometer, which measured the current from the thermo-couple, depended upon the length of time that light was allowed to pass through the slit, a pendulum switch was made which would light and turn out the electric lamp, which illuminated the slit, at predetermined intervals. With this apparatus, results were obtained which were consistent with those obtained with the photometer, and the results could be repeated.

Fig. 47 shows the data obtained by measuring a film with the photometer, curve *A*, and with the thermo-couple, curve *B*. In

this article all ordinates represent intensities of transmitted light. These two curves are consistent as regards general shape and position of the minima points of the curves. Since intensities of transmitted light are plotted, the minima of the curves correspond to the maxima intensities of the spectra. Inspection will show that curve *B* is not the exact duplicate of curve *A*; the ratios of the ordinates at long wave-lengths are not the same as at shorter wave-lengths. This lack of similarity did not exist in many of the comparisons and was, quite likely, due either to eye fatigue or else to the gradual warming up of the plate under successive exposures to the light which illuminated the slit.

Fig. 48 shows three curves corresponding to the decay of phos-

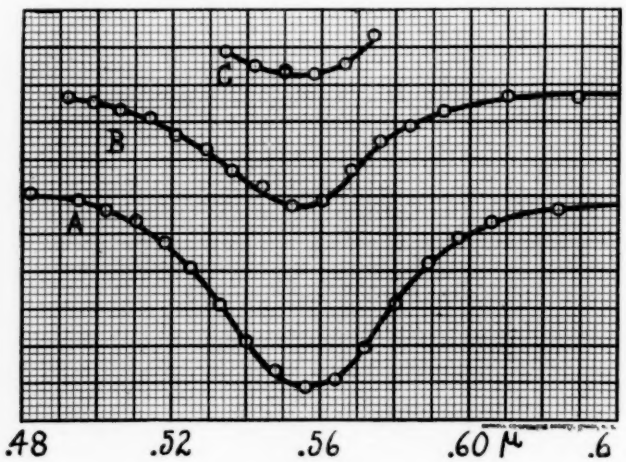


Fig. 48.

phorescence. In curve *A*, the Sidot blende was excited for 9¾ sec. and the plate was exposed for 8½ sec. immediately after excitation. Then the powder was exposed for about one minute to infra-red rays and the process repeated. In curve *B* the powder was excited for 21 sec., allowed to decay for 14 sec., then the plate was exposed for 15 sec. In curve *B* the x-axis was raised so that curve *B* would not intersect with curve *A*. In curve *C*, the excitation was 5½ min., the decay 1½ min. and the plate was then exposed for one minute. The total time to produce the negative from which curve *C* was made was 72 hours. The negative was faint and the

film was somewhat fogged, but remeasurements on the film always gave approximately the same curve. In fact, curve *C* is the average of several remeasurements. The minima of these curves occur at wave-length $\mu = 0.555 \pm 0.003$.

The bend in the curve of decay of the phosphorescence of Sidot blende occurs between 10 and 20 sec. after the end of excitation and is more pronounced the longer the excitation. Hence curve *A*, in Fig. 48, is due mostly to the light corresponding to the decay before the bend, while curve *B* corresponds to conditions near the bend, and curve *C* corresponds to conditions far beyond the bend. Or in terms of the two band theory, curve *A* corresponds mainly to band 1; curve 2, to bands 1 and 2; and curve 3 to band 2 almost entirely. This set of curves shows no change in the maxima of the spectra, and no set was obtained which showed any appreciable change.

Because Balmain's paint, a powder on which data for a previous article were obtained, shows a more pronounced bend in the decay curve than Sidot blende, two curves, Fig. 49, were obtained showing

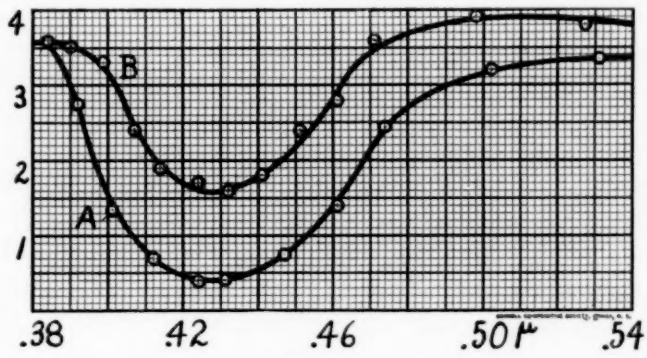


Fig. 49.

the spectrum before and after the bend. For each curve, the excitation was 5 min. For curve *A*, the plate was exposed 20 sec. immediately after excitation. For curve *B*, the phosphorescence was allowed to decay 1½ min., then the plate was exposed for one minute. No shift in the minima of the curves is evident, while a decided shift in the minima or a decided change in the shape of the curves would be expected if the two-band theory is correct.

The effect of infra-red radiations in suppressing phosphorescence and fluorescence is well known. Nichols and Merritt[1] found that all parts of the fluorescence spectrum were suppressed in the same ratio. As a check on the above work and on the present work, and because, on the basis of the two-band theory, all available data lead to an assumption that one band is suppressed more than the other, several runs were made in which the fluorescence spectrum of Sidot blende under the influence of infra-red rays was photographed. These rays were obtained, as in the whole work, from a 16 c.p. lamp held two inches from the powder. The visible portion of light was screened off by means of thin rubber.

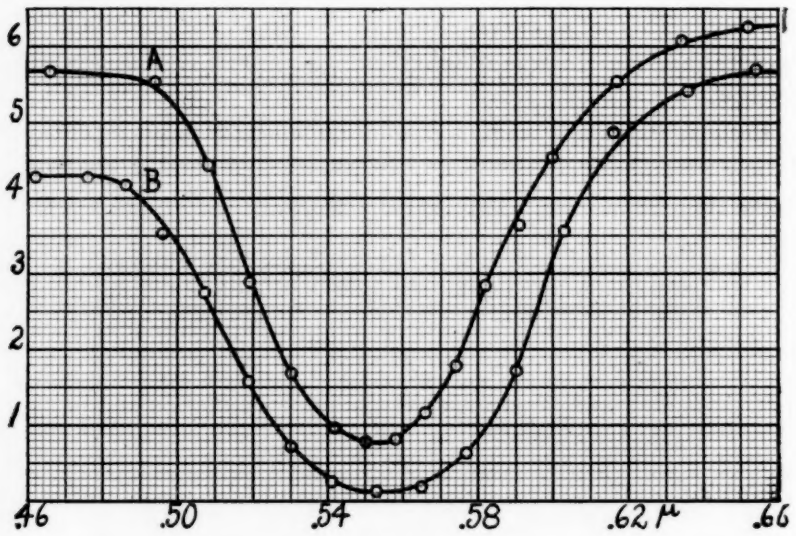


Fig. 50.

In Fig. 50 curve *A* corresponds to the fluorescence spectrum without infra-red excitation, and curve *B*, with infra-red. The exposure of the plate in the latter was twice as long as in the former case. The minimum is not changed appreciably from $\mu = 0.555$, and the curves correspond very well except at short wave-lengths.

In Fig. 51 curve *A* corresponds to the fluorescence spectrum without infra-red; curve *B*, with infra-red; and curve *C* corresponds to the phosphorescence spectrum just after excitation and is added

[1] PHYS. REV., Vol. XXV., No. 5, Nov., 1907. p. 362.

for ease of comparison. In each case the minimum of the curve occurs at $\mu = 0.555$ approximately.

The only effect of infra-red excitation on the fluorescence spectrum, according to all of the curves obtained, is to decrease the intensity of the band, but not to change its general shape. This result is in accordance with that found by Nichols and Merritt and is not in favor of the two-band theory of decay.

It is known that bands in the spectrum of fluorescent substances

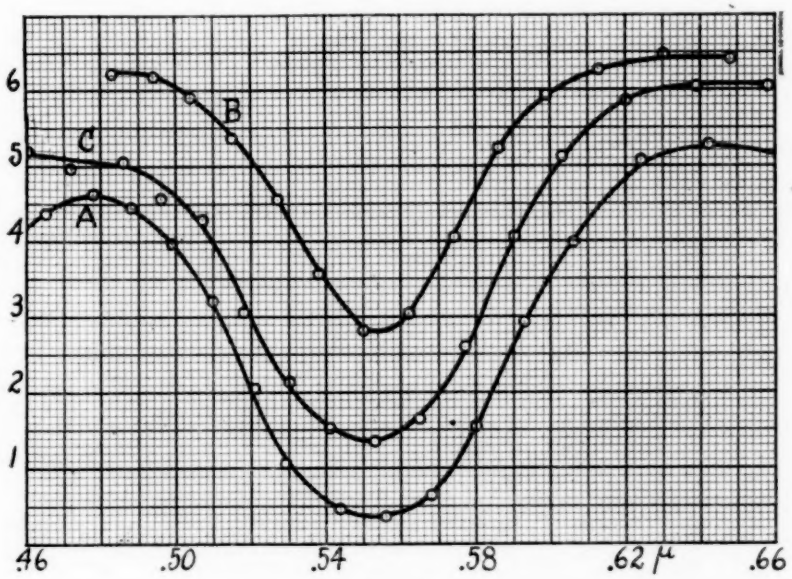


Fig. 51.

grow brighter or die out with changes in the temperature of the substance. This effect is due to the temperature change alone since many of the substances will show normal spectra when the temperature is brought back to normal. Some runs were made to see if any change could be detected in the fluorescence band of Sidot blende at different temperatures higher than normal. It is well known that the phosphorescence decay varies in rapidity with change of temperature and this could be easily explained by means of the two-band theory of decay.

Fig. 52 shows four curves corresponding to the fluorescence of Sidot blende at different temperatures. In each case the length of

excitation was varied so as to give, approximately, negatives of equal average density, hence the dimming of the band at higher temperatures is not evident, though it occurred, the powder practically ceasing to exhibit fluorescence when the temperature was raised sufficiently. When the temperature was lowered, the powder

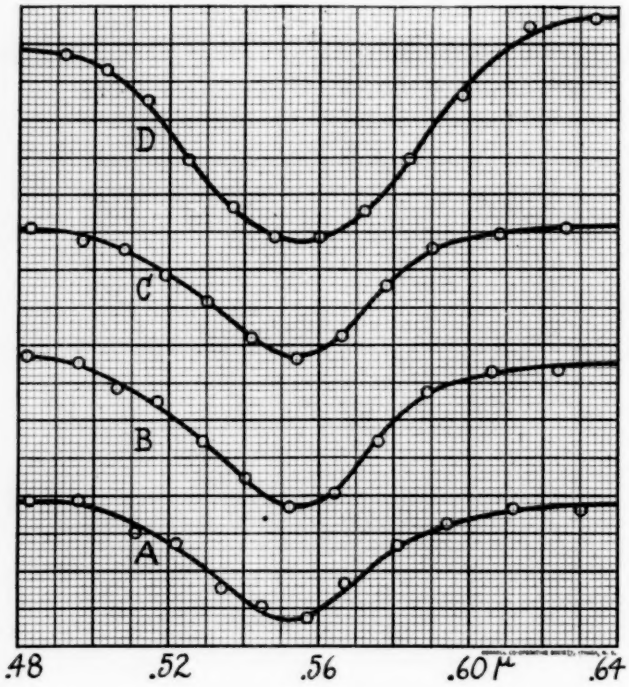


Fig. 52.

would again show the same spectrum as before if a certain critical temperature was not reached. The x-axis is changed for each curve so that the points may be entirely distinct from one another. Curves A, B, C and D were obtained at temperatures 22°, 67°, 88° and 120° respectively. No shifting of the minimum is evident.

DISCUSSION OF RESULTS AND CONCLUSIONS.

The accuracy of measurements made with a non-direct method, as the one above, is not great. Conclusions must be drawn from the indications of many runs, rather than from the too exact inter-

pretation of a single run. A general survey of the curves shown will lead to the conclusion that the minima of all of the curves occur within the limits, $\lambda = 0.555\mu \pm 0.003$. These limits were seldom exceeded and the variations were not consistent with each other. For some sets of curves, the limits could be contracted to $\pm 0.002\mu$ or possibly to $\pm 0.001\mu$. Hence, if the maximum of the band changed under any of the conditions it must have been within the limits $\pm 0.003\mu$ and probably within even smaller limits. From certain considerations, such as the bend in the decay curve of phosphorescence, and the smooth symmetrical shape of the whole band, one would expect, if the two-band theory is correct, a considerable change in the band under the conditions studied. No changes were found that were not explained by the limitations of the method.

Hence the following conclusions are drawn from the work above:

1. That the fluorescence and phosphorescence bands of Sidot blende coincide with each other.

2. That no change in the position of the band of phosphorescence occurs with decay.

3. That no change in the position of the band of fluorescence occurs under the action of infra-red rays.

4. That no change in the position of the band of fluorescence occurs with a change in temperature of the powder.

5. That no evident change in the shape of the band was found under the above conditions.

6. That no change in the position or shape of the band of phosphorescence of Balmain's paint occurs with decay.

7. That the two-band theory of the decay of phosphorescence is not sustained.

PHYSICAL LABORATORY,
CORNELL UNIVERSITY,
August 22, 1910.

PROCEEDINGS

OF THE

AMERICAN PHYSICAL SOCIETY.

MINUTES OF THE FIFTY-FOURTH MEETING.

THE Thanksgiving Meeting of the American Physical Society was held in the Ryerson Physical Laboratory of the University of Chicago on Saturday, November 26, 1910.

In the absence of the secretary, Dr. Jakob Kunz was elected secretary for the session.

The following papers were read:

Limitations Imposed by Slip and Inertia Terms upon Stokes' Law for the Motion of Spheres through Liquids. H. D. ARNOLD.

Echoes in an Auditorium. F. R. WATSON.

The Hall Effect and Some Allied Effects in Alloys. ALPHEUS W. SMITH.

The Conduction of Electricity through Gases at various Temperatures. ROBERT F. EARHART.

The Production of Light by Canal Rays. GORDON S. FULCHER.

On the Ionization of Gases by the Alpha Particles from Polonium. T. S. TAYLOR.

On the Initial Velocity of Electrons emitted by Alkali Metals as a Function of the Wave-length of Light. JAKOB KUNZ.

The Increase in the Positive Potentials assumed by Metals under the Influence of Ultra-violet Light. R. A. MILLIKAN.

The Photo-electric Potentials of Aluminum as a Function of the Wave-Length of the Incident Light. J. R. WRIGHT.

The Electrical Properties of Light-positive and Light-negative Selenium. F. C. BROWN.

A New Formula for the Vapor Tension of Water between 0° and 200° C. K. E. GUTHE and A. G. WORTHING.

A Null Method for Measuring Diamagnetic Susceptibility, and some Results obtained with it. C. E. MENDENHALL and W. F. LENT.

A Comparison of the Influence of Planes of Transverse Section on the Magnetic Properties of Iron and of Nickel Bars. E. H. WILLIAMS. Introduced by A. P. Carman.

The Spectrum of the Spark under Pressure and an Application of the Results to the Spectrum of the Chromosphere. HENRY G. GALE and WALTER S. ADAMS, Ryerson Physical Laboratory.

Results of Measurement on the Ultra-red Spectra of Sn, Pb, As, Bi, and Sb. H. M. RANDALL.

On the Emissive power of Wedge-shaped Apertures and their Use in Temperature Measurements. C. E. MENDENHALL.

Valve-action of Al and Mg and their Alloys. C. NUSBAUM.

Luminous Efficiency of Incandescent Lamp Filaments. W. E. FORSYTHE.

The Effect of Temperature on the Di-electric Strength of Porcelain Insulators. GEO. O. WEIMER..

The Kinetic Pressure-drop Correction in the Transpiration Method for Gas Viscosity. (By title.) WILLARD J. FISHER.

On the Free Vibrations of a Lecher System using a Blondlot Oscillator. F. C. BLAKE and Miss RUPPERSBERG.

On the Free Vibrations of a Lecher System using a Lecher Oscillator. F. C. BLAKE and CHARLES SHEARD.

The Distribution of Discharge between a Point and Plane under Varying Pressures. ROBT. F. EARHART and F. W. POTE.

Elastic Properties of Bismuth Wire. K. E. GUTHE and J. E. HARRIS.

Some Developments in the Construction and Use of the Optical Pyrometer. C. E. MENDENHALL.

The Theory of Light-positive and Light-negative Selenium. F. C. BROWN.

Experimental Determination of the Temperature in a Fog Chamber immediately after Expansion. E. K. CHAPMAN.

On the Absorption of Gamma Rays of Radium by Solids and Liquids. (By title.) S. J. ALLEN.

Professor A. P. Carman took the chair during the absence of President Crew in the afternoon session.

The members of the American Physical Society were invited by the University Club to luncheon. A vote of thanks to the University of Chicago for their hospitality proposed by Dr. Watson was unanimously carried. The meeting was closed at five o'clock.

DR. JAKOB KUNZ,
Secretary pro tempore.

NEW BOOKS.

A Text Book of Physics. By H. E. HURST and R. T. LATTEY. New York: D. Van Nostrand Company, 1910. Pp. ix + 638. Price, $3.00.

Physics. By C. R. MANN and G. R. TWISS. (Revised edition.) New York: Scott, Foresman and Company, 1910. Pp. x + 424.

An Introduction to Thermodynamics. By JOHN MILLS. Boston: Ginn and Company, 1910. Pp. viii + 136. Price, $2.00.

Gesammelte Abhandlungen. By FRIEDRICH KOHLRAUSCH. Leipzig: Johann Ambrosius Barth, 1910. Pp. xxxv + 1108. Price, M. 25.

Das Kristallisationsmikroskop. By O. LEHMAN. (Festschrift zur Feier des Dreiundfünfzigsten Geburtstages Friedrich II. von Baden.) Braunschweig: Friedrich Vieweg und Sohn, 1910. Pp. 112.

Grundzüge der Mathematisch-Physikalischen Akustik. By Dr. ALFRED KALAHNE. Leipzig: B. G. Teubner, 1910. Pp. vii + 130. Price, M. 3.20.

Lehrbuch der Kristallphysik. By WOLDEMAR VOIGT. Leipzig: B. G. Teubner, 1910. Pp. xxiv + 964. Price, M. 30.

Prinzipien der Atomdynamik. By Dr. J. STARK. Leipzig: S. Hirzel, 1910. Pp. x + 124. Price, M. 3.20.

Annuaire Pour L'An 1911. Publie par le Bureau des Longitudes. Paris: Gauthier-Villars, 1910. Pp. vii + 639.